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Johnson et al.

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(54) **HEAD TRANSDUCER WITH MULTIPLE RESISTANCE TEMPERATURE SENSORS FOR HEAD-MEDIUM SPACING AND CONTACT DETECTION**

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Related U.S. Application Data

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(51) **Int. Cl.**

G11B 5/02 (2006.01)
G11B 5/60 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***G11B 5/607*** (2013.01); ***G01K 13/00*** (2013.01); ***G11B 5/024*** (2013.01); ***G11B 5/6011*** (2013.01); ***G11B 5/6076*** (2013.01); ***G11B 20/10*** (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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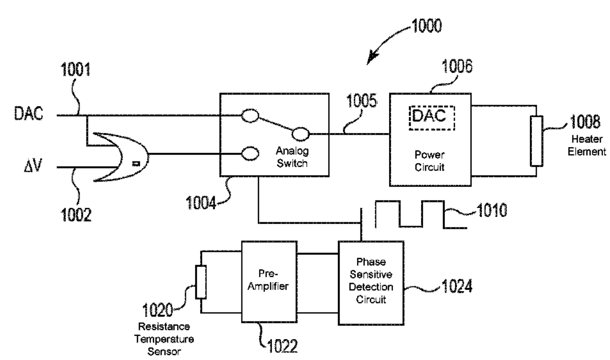
(57) **ABSTRACT**

A head transducer, configured to interact with a magnetic recording medium, includes a first sensor having a temperature coefficient of resistance (TCR) and configured to produce a first sensor signal, and a second sensor having a TCR and configured to produce a second sensor signal. One of the first and second sensors is situated at or near a close point of the head transducer in relation to the magnetic recording medium, and the other of the first and second sensors spaced away from the close point. Circuitry is configured to combine the first and second sensor signals and produce a combined sensor signal indicative of one or both of a change in head-medium spacing and head-medium contact. Each of the sensors may have a TCR with the same sign (positive or negative) or each sensor may have a TCR with a different sign.

22 Claims, 22 Drawing Sheets



(51) **Int. Cl.**

G11B 20/10	(2006.01)
G01K 13/00	(2006.01)
G11B 5/024	(2006.01)

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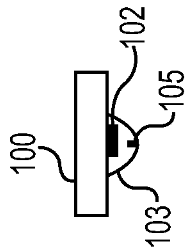


Fig. 2

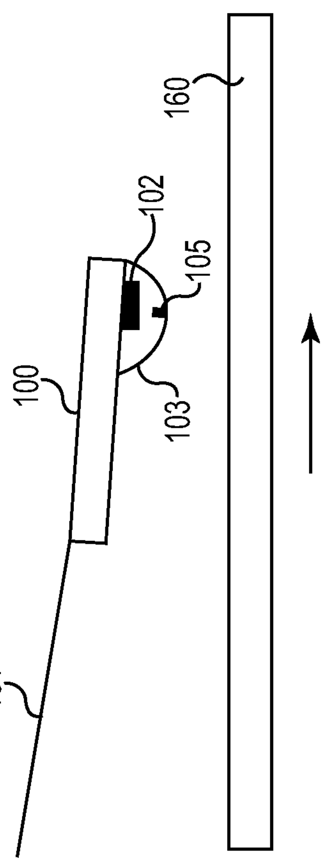


Fig. 1

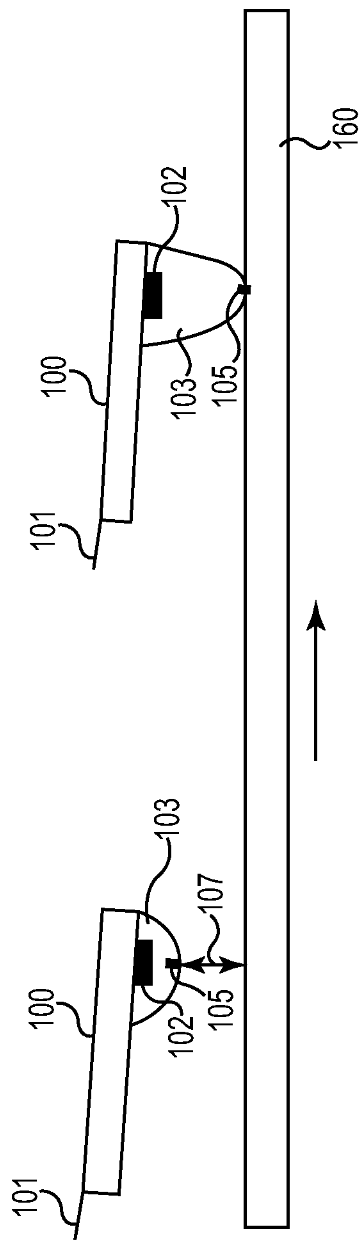
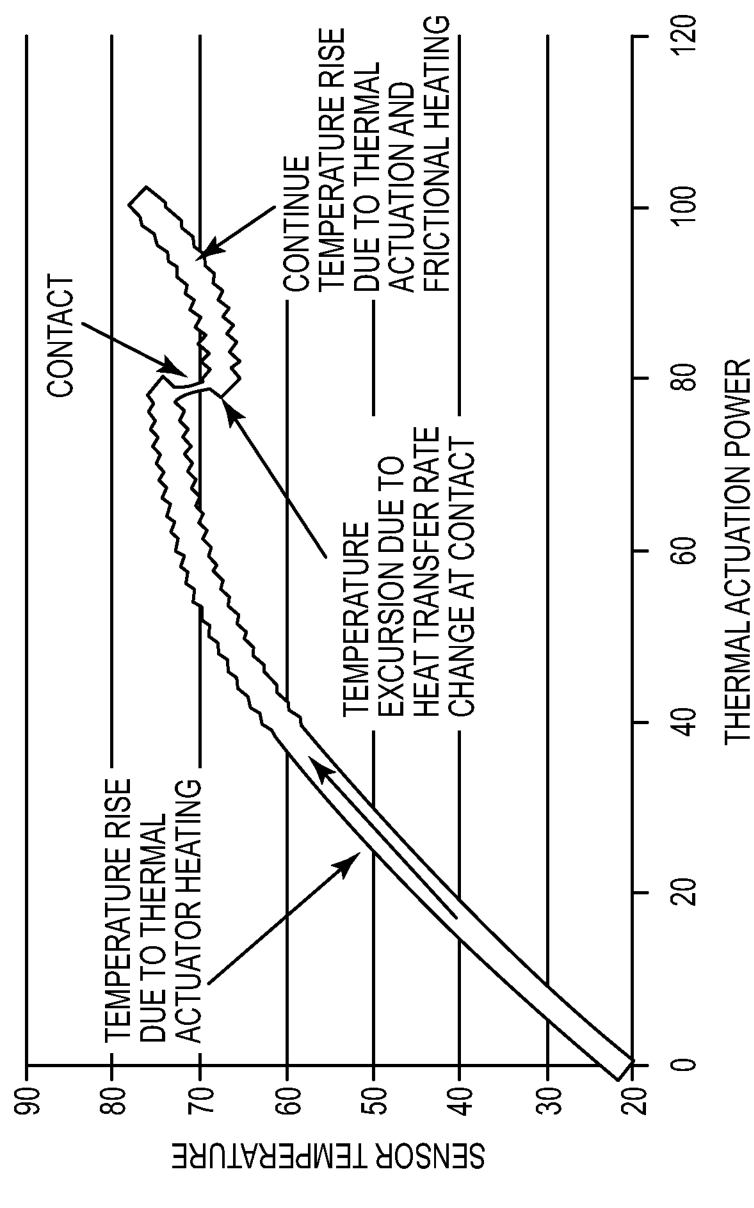


Fig. 3



SENSOR TEMPERATURE
90
80
70
60
50
40
30
20
THERMAL ACTUATION POWER
0
20
40
60
80
100
120
TEMPERATURE RISE DUE TO THERMAL ACTUATOR HEATING
CONTACT
TEMPERATURE EXCURSION DUE TO HEAT TRANSFER RATE CHANGE AT CONTACT
CONTINUE TEMPERATURE RISE DUE TO THERMAL ACTUATION AND FRICTIONAL HEATING

Fig. 4A

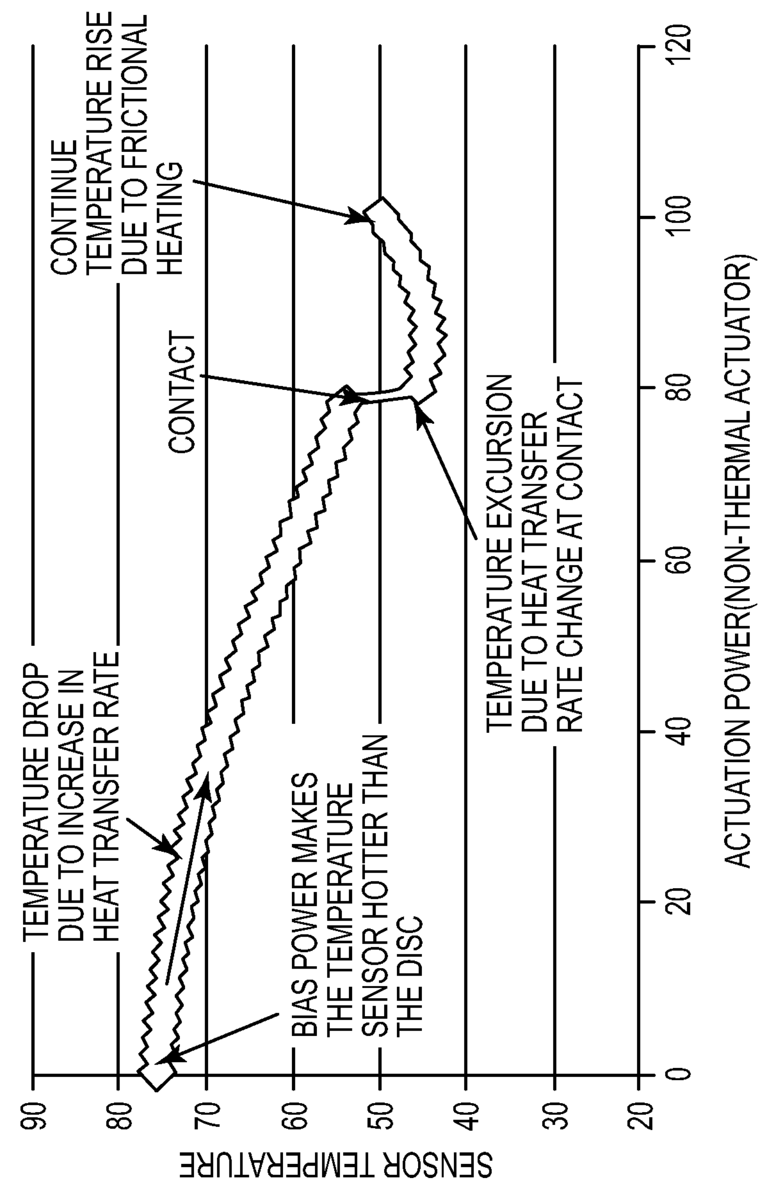

SENSOR TEMPERATURE
90
80
70
60
50
40
30
20
0
20
40
60
80
100
120
ACTUATION POWER(NON-THERMAL ACTUATOR)
TEMPERATURE DROP DUE TO INCREASE IN HEAT TRANSFER RATE
BIAS POWER MAKES THE TEMPERATURE SENSOR HOTTER THAN THE DISC
CONTACT
TEMPERATURE EXCURSION DUE TO HEAT TRANSFER RATE CHANGE AT CONTACT
CONTINUE TEMPERATURE RISE DUE TO FRICTIONAL HEATING

Fig. 4B

Fig. 5A

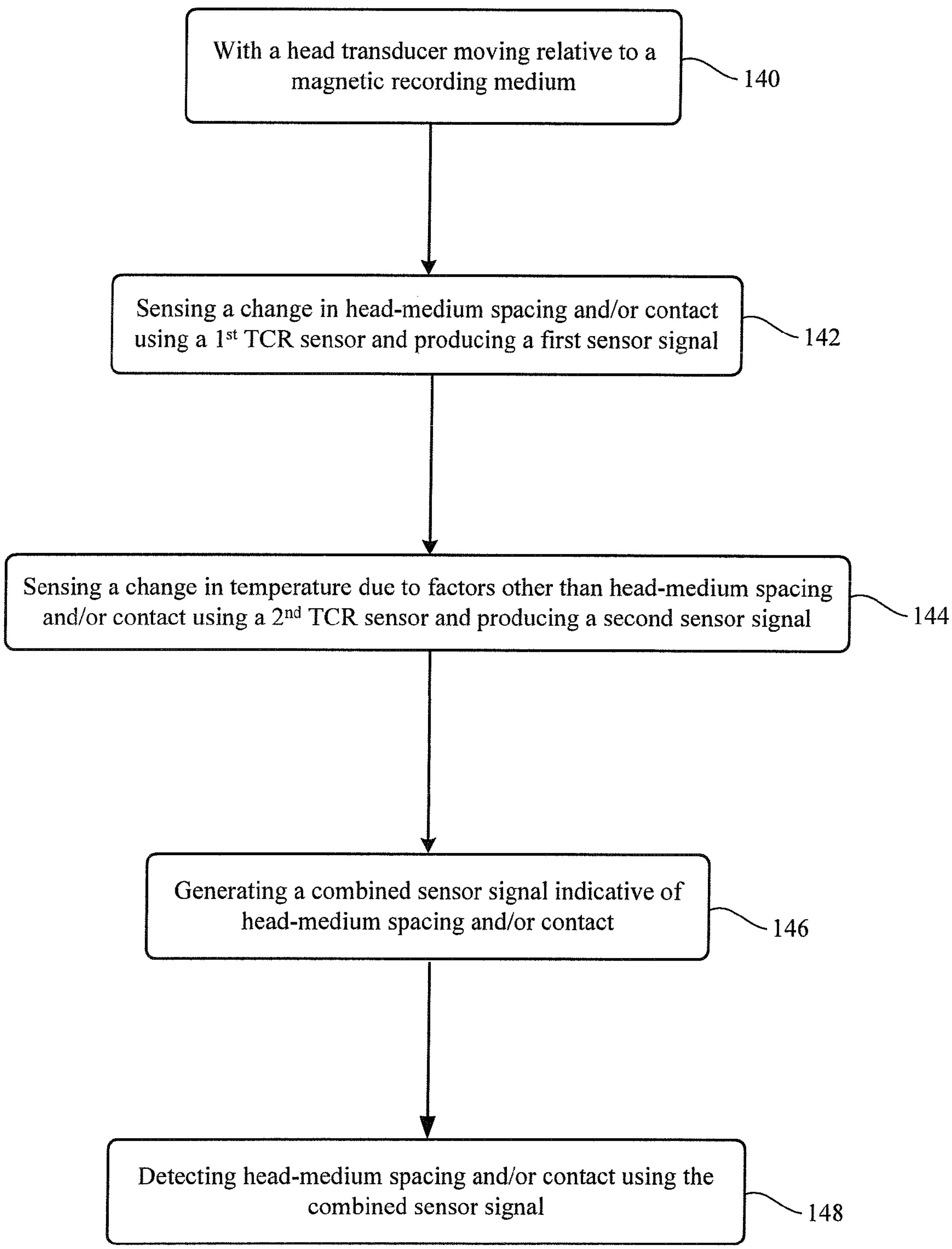

With a head transducer moving relative to a magnetic recording medium
140
Sensing a change in head-medium spacing and/or contact using a 1st TCR sensor and producing a first sensor signal
142
Sensing a change in temperature due to factors other than head-medium spacing and/or contact using a 2nd TCR sensor and producing a second sensor signal
144
Generating a combined sensor signal indicative of head-medium spacing and/or contact
146
Detecting head-medium spacing and/or contact using the combined sensor signal
148

Fig. 5B

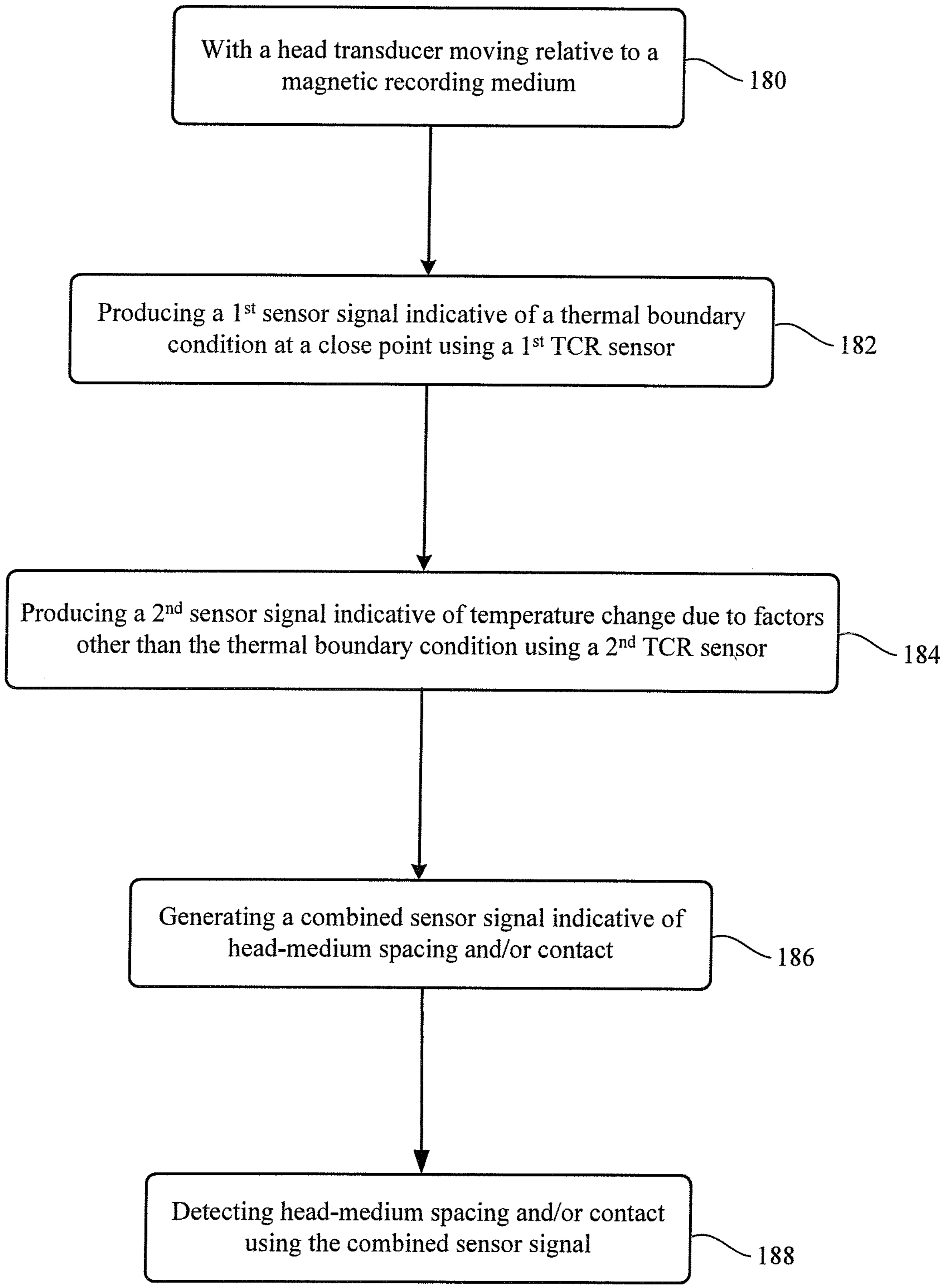

With a head transducer moving relative to a magnetic recording medium
180
Producing a 1st sensor signal indicative of a thermal boundary condition at a close point using a 1st TCR sensor
182
Producing a 2nd sensor signal indicative of temperature change due to factors other than the thermal boundary condition using a 2nd TCR sensor
184
Generating a combined sensor signal indicative of head-medium spacing and/or contact
186
Detecting head-medium spacing and/or contact using the combined sensor signal
188

Fig. 6A

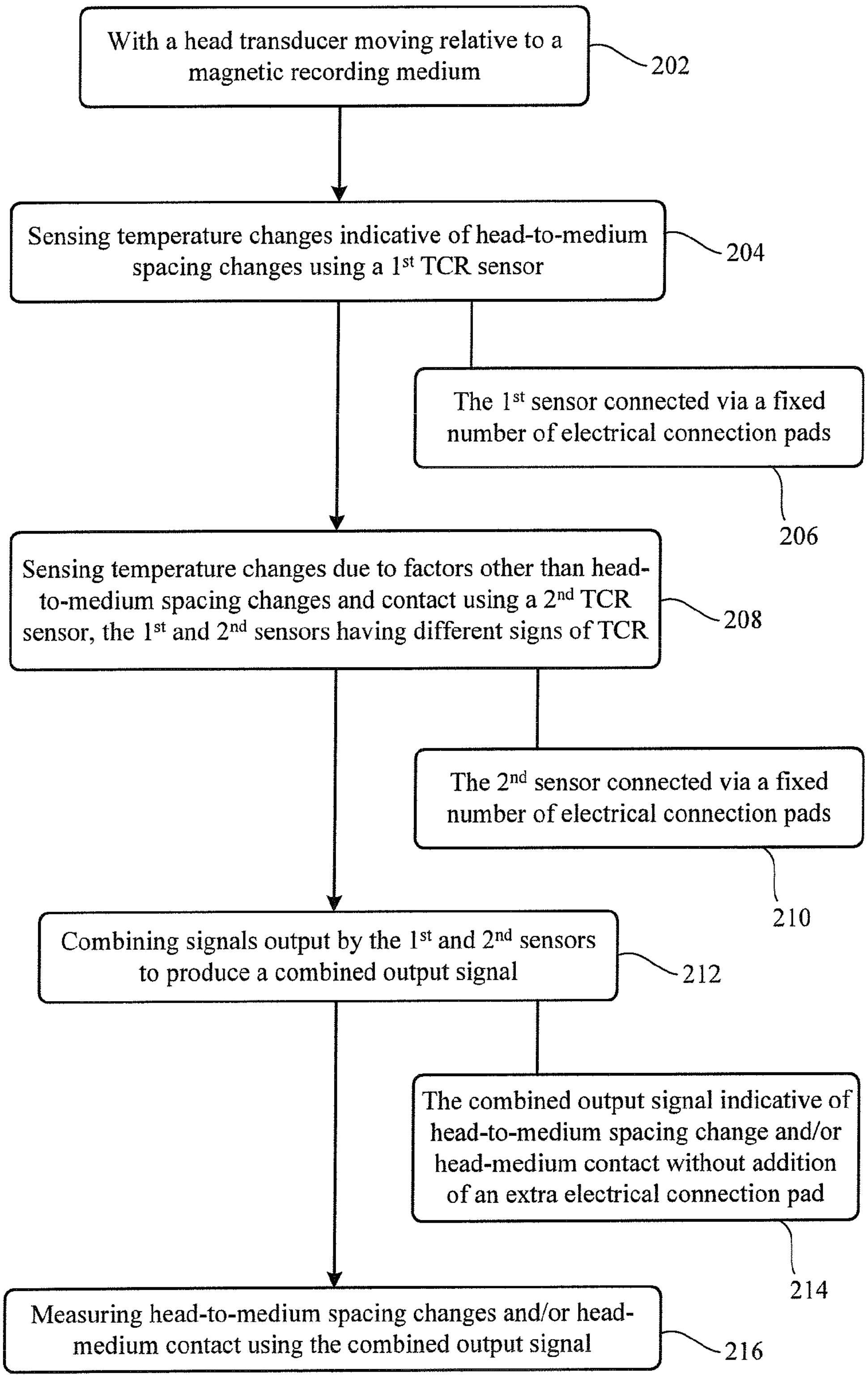
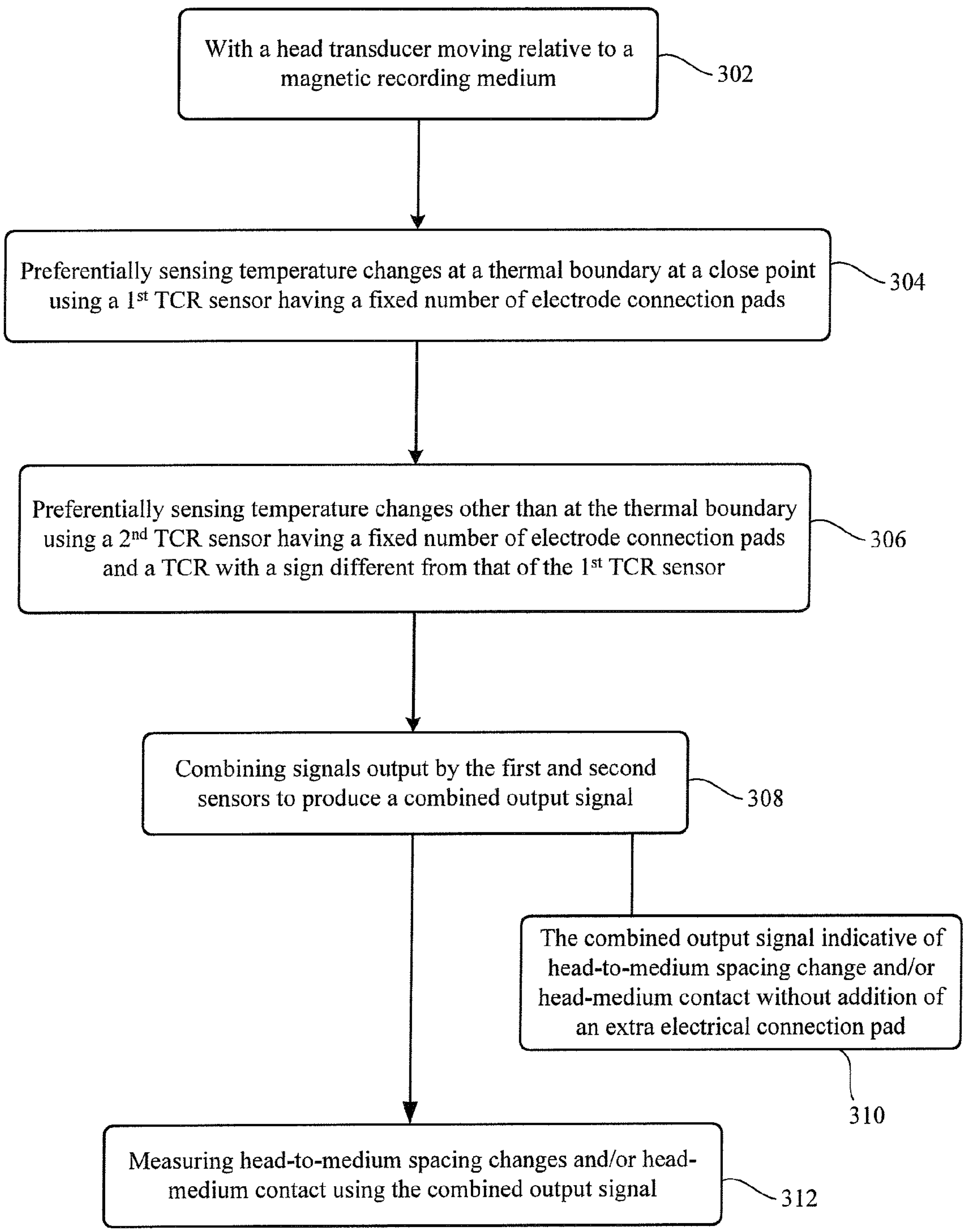

With a head transducer moving relative to a magnetic recording medium
202
Sensing temperature changes indicative of head-to-medium spacing changes using a 1st TCR sensor
204
The 1st sensor connected via a fixed number of electrical connection pads
206
Sensing temperature changes due to factors other than head-to-medium spacing changes and contact using a 2nd TCR sensor, the 1st and 2nd sensors having different signs of TCR
208
The 2nd sensor connected via a fixed number of electrical connection pads
210
Combining signals output by the 1st and 2nd sensors to produce a combined output signal
212
The combined output signal indicative of head-to-medium spacing change and/or head-medium contact without addition of an extra electrical connection pad
214
Measuring head-to-medium spacing changes and/or head-medium contact using the combined output signal
216

Fig. 6B


With a head transducer moving relative to a magnetic recording medium
302
Preferentially sensing temperature changes at a thermal boundary at a close point using a 1st TCR sensor having a fixed number of electrode connection pads
304
Preferentially sensing temperature changes other than at the thermal boundary using a 2nd TCR sensor having a fixed number of electrode connection pads and a TCR with a sign different from that of the 1st TCR sensor
306
Combining signals output by the first and second sensors to produce a combined output signal
308
The combined output signal indicative of head-to-medium spacing change and/or head-medium contact without addition of an extra electrical connection pad
310
Measuring head-to-medium spacing changes and/or head-medium contact using the combined output signal
312

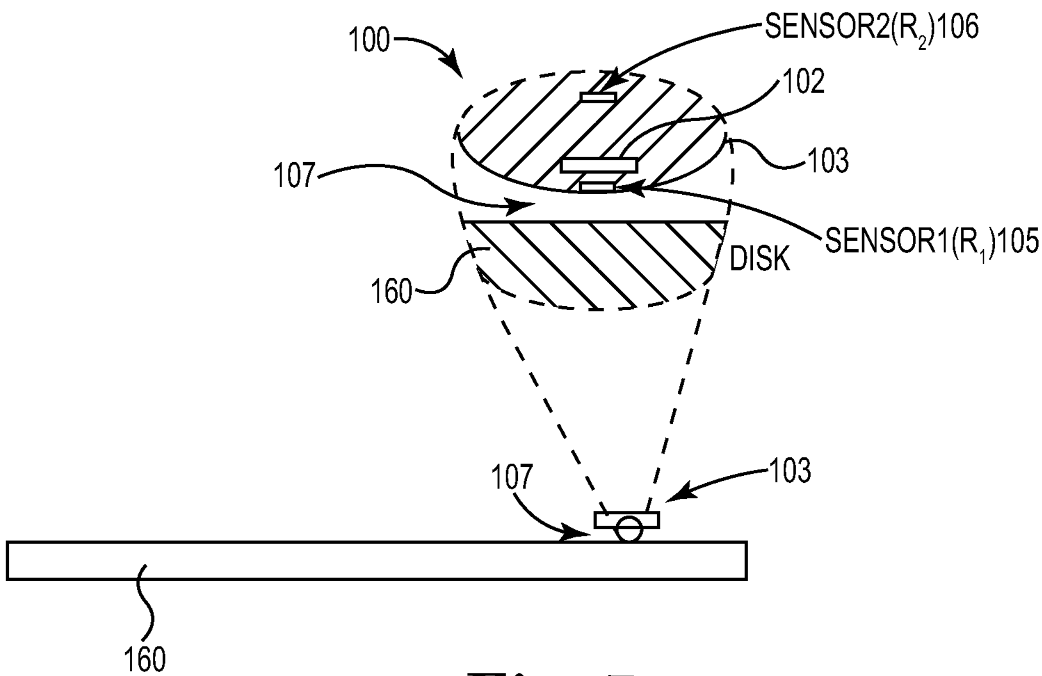

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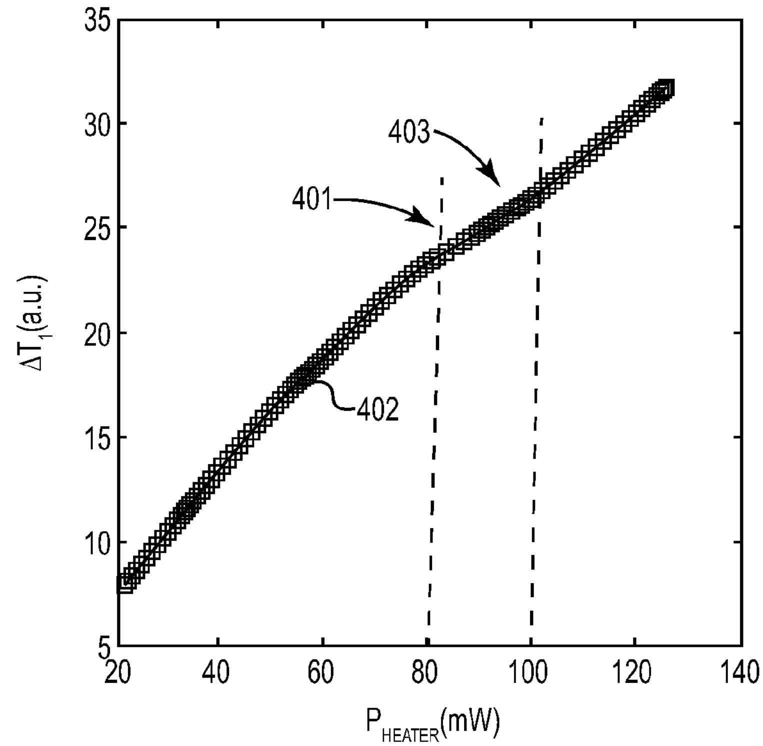
Fig. 7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120
140
ΔT1(a.u.)
PHEATER(mW)
401
402
403

Fig. 8

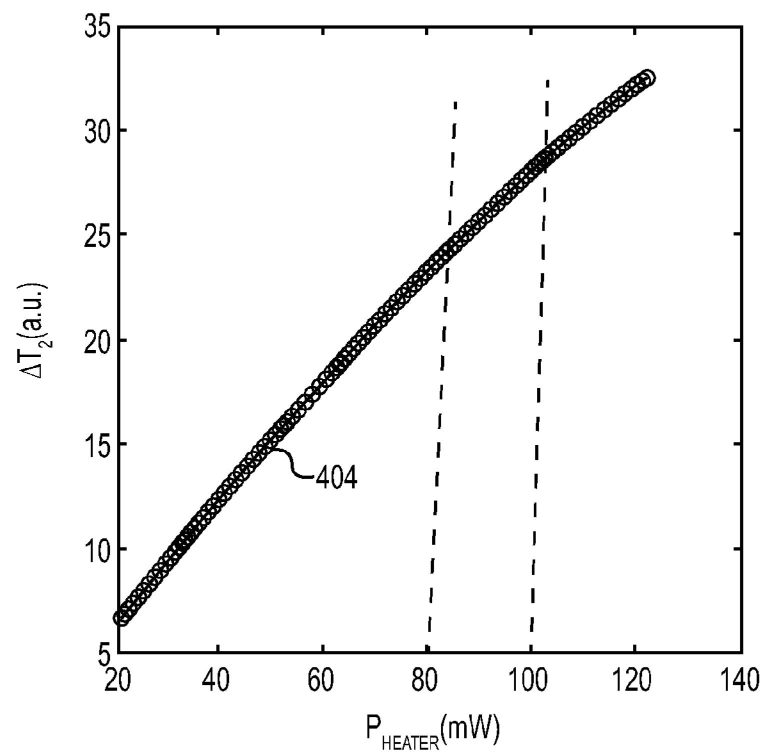

35
30
25
20
15
10
5
20
40
60
80
100
120
140
ΔT2(a.u.)
PHEATER(mW)
404

Fig. 9

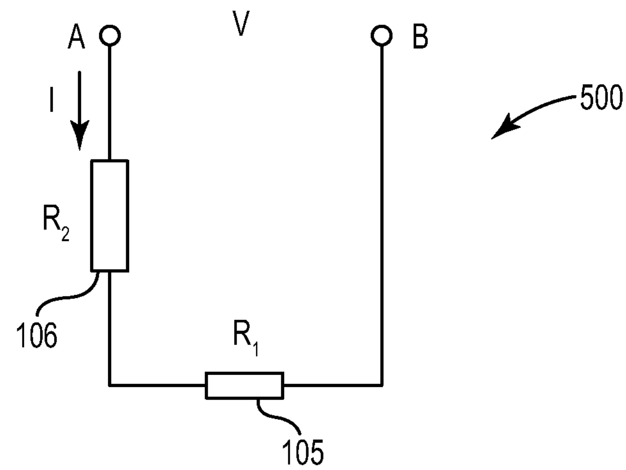

A
V
B
I
500
R2
106
R1
105

Fig. 10

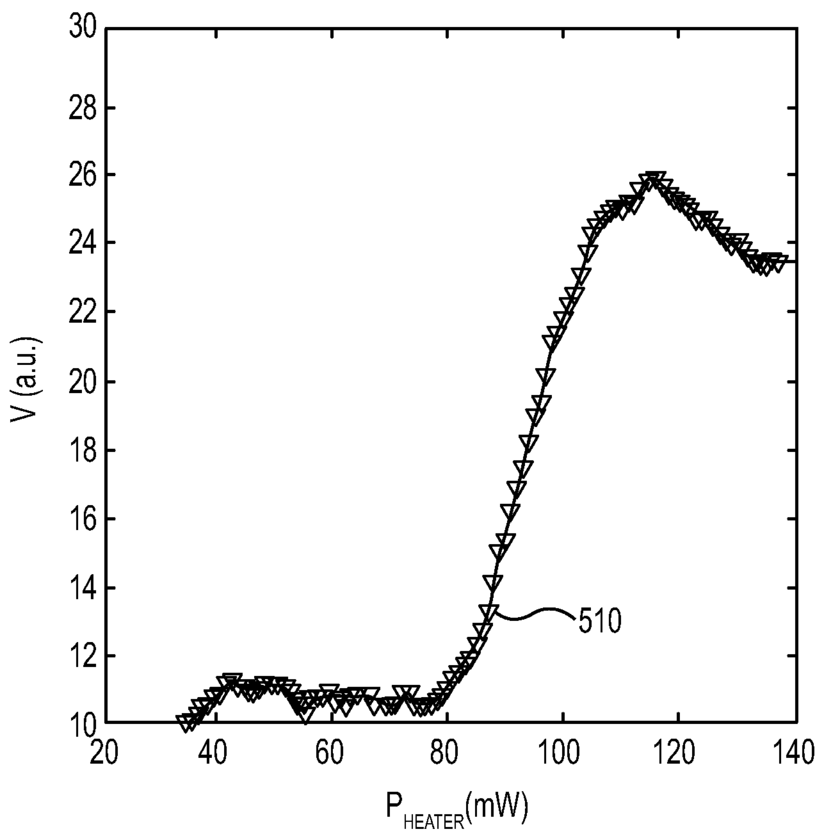

30
28
26
24
22
20
18
16
14
12
10
V (a.u.)
510
20
40
60
80
100
120
140
PHEATER(mW)

Fig. 11

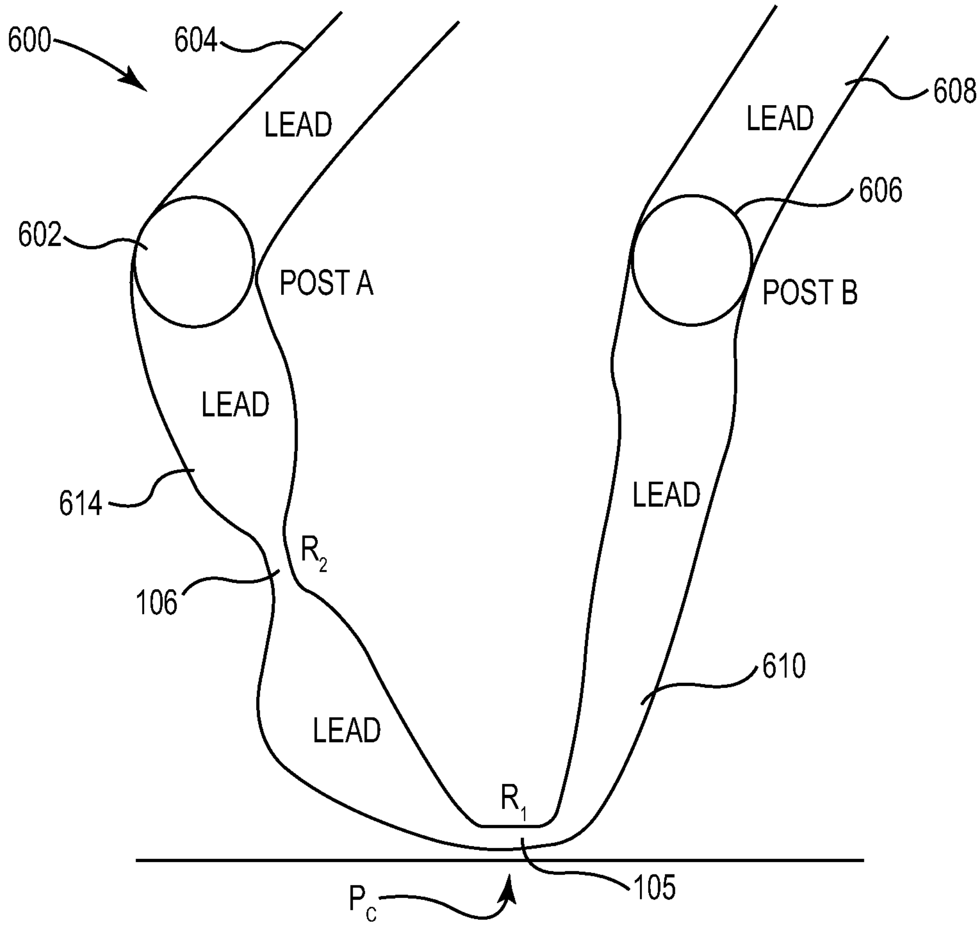

600
604
LEAD
608
LEAD
602
606
POST A
POST B
LEAD
614
LEAD
R_2
106
610
LEAD
R_1
105
P_C

Fig. 12

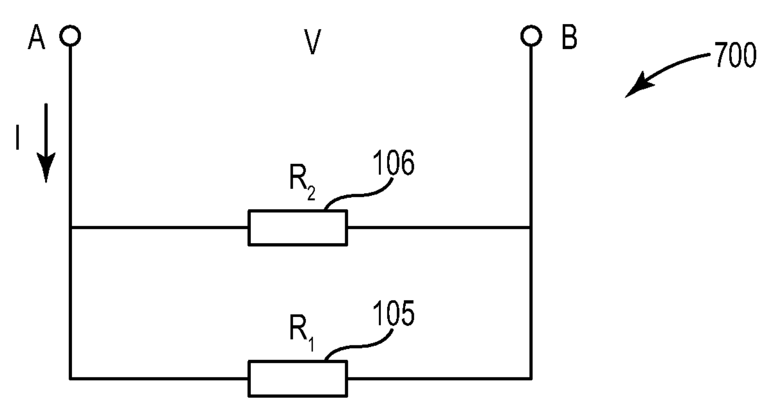

A
V
B
700
I
R_2
106
R_1
105

Fig. 13

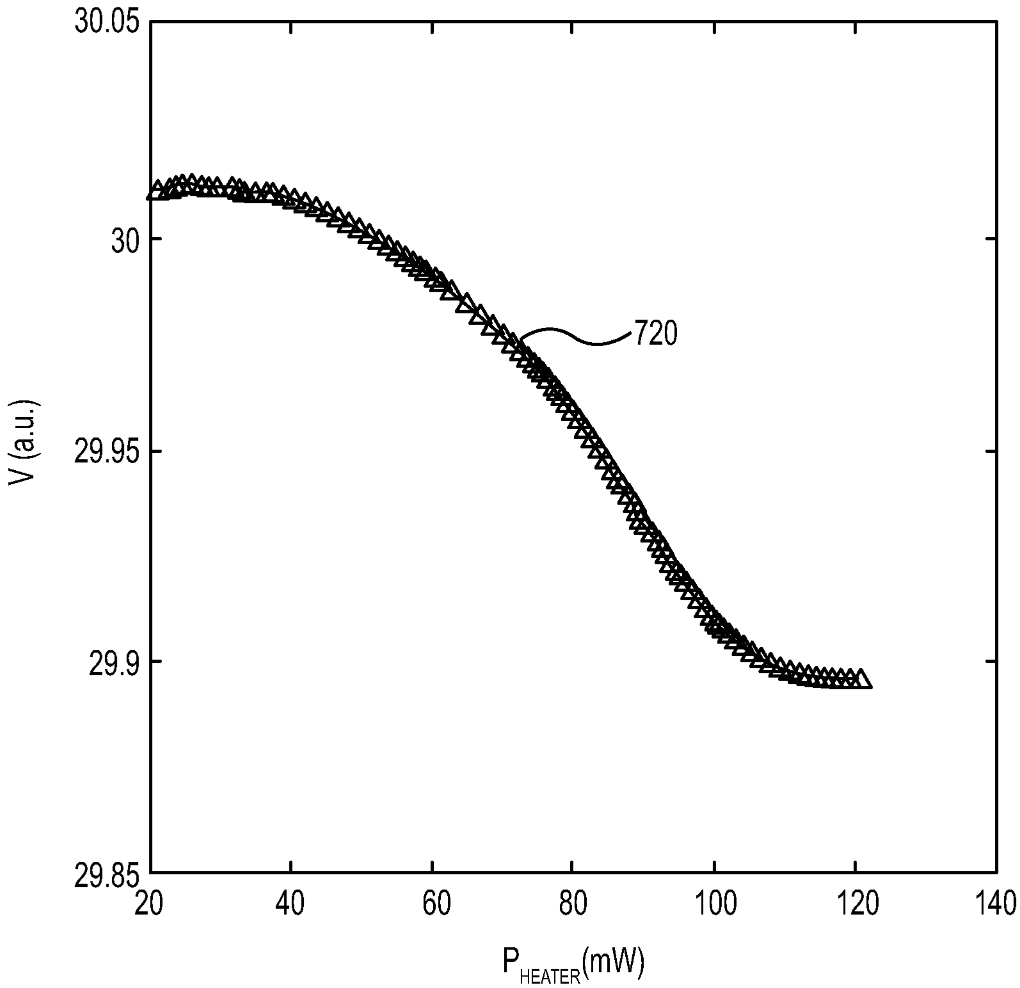


Fig. 14

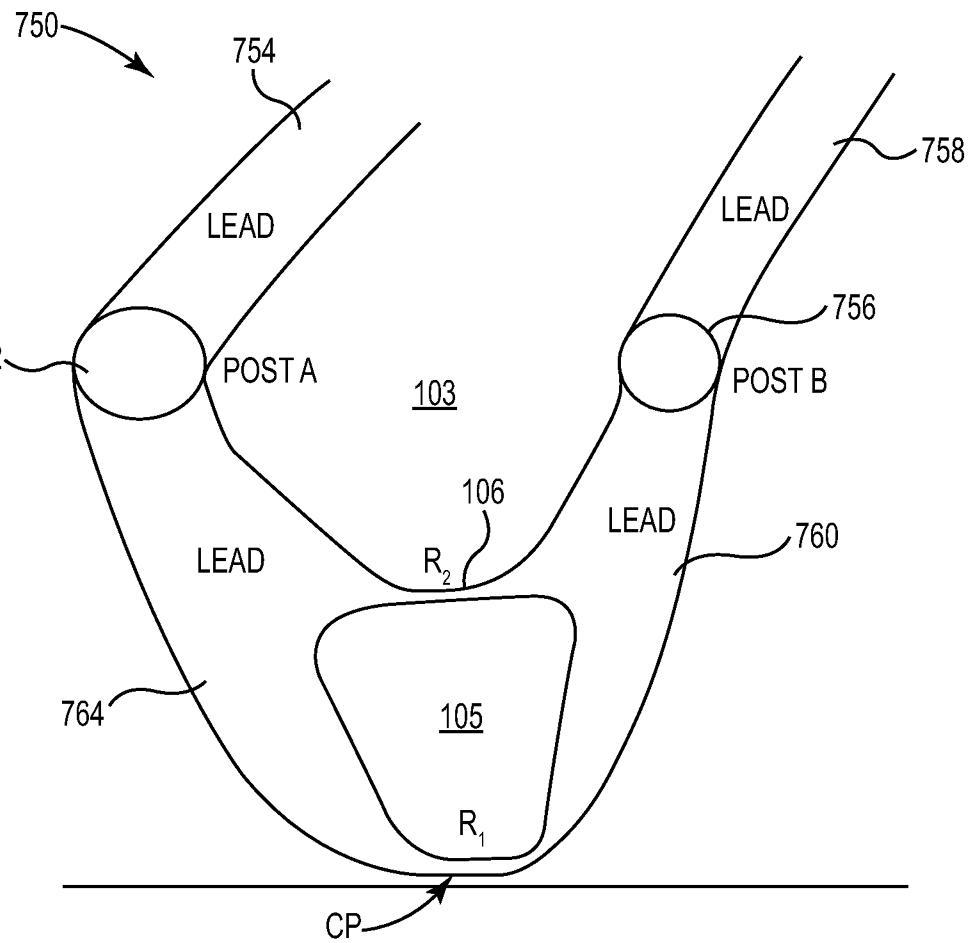

750
754
LEAD
758
LEAD
756
752
POST A
103
POST B
106
LEAD
R2
LEAD
760
105
764
R1
CP

Fig. 15

Fig. 16A

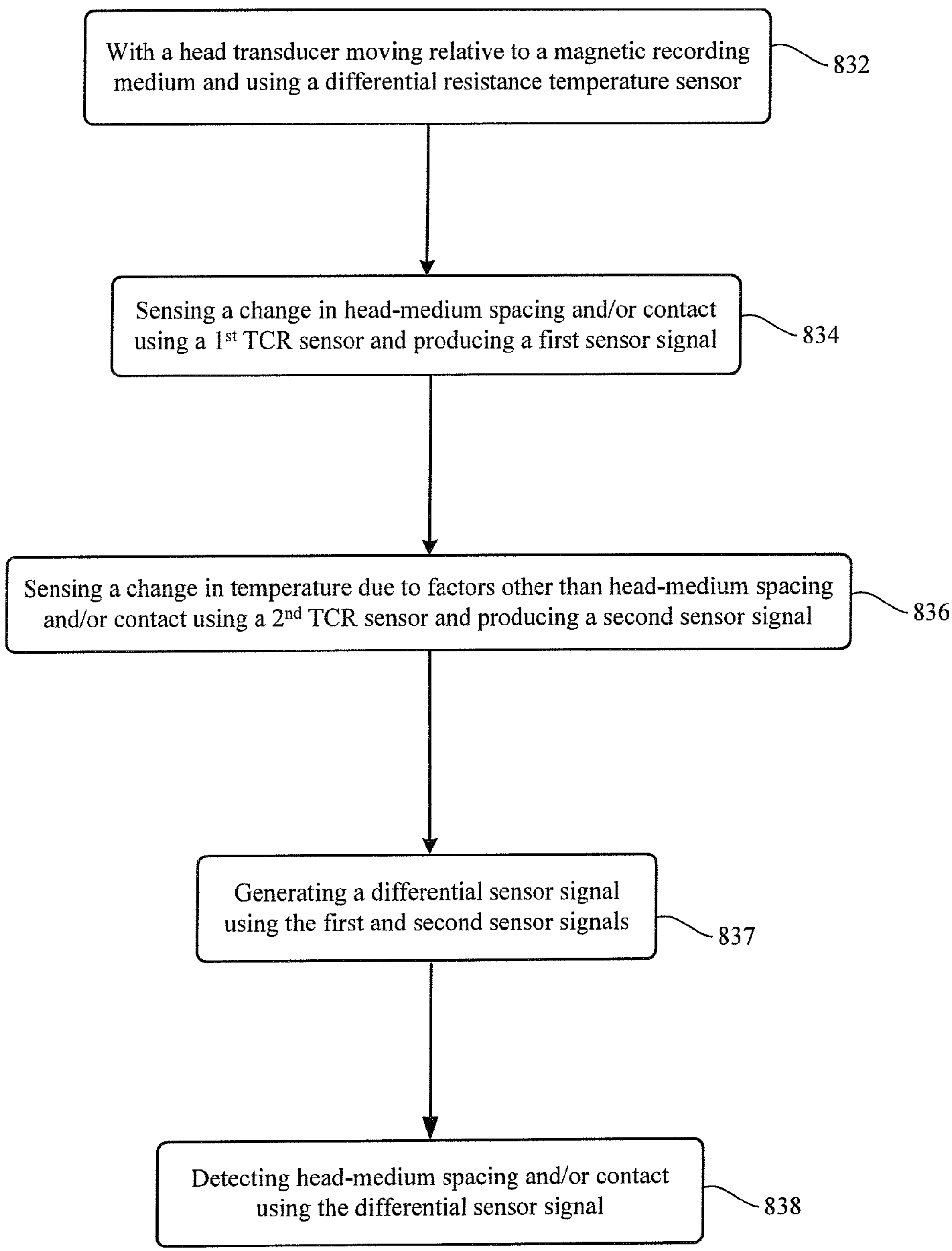
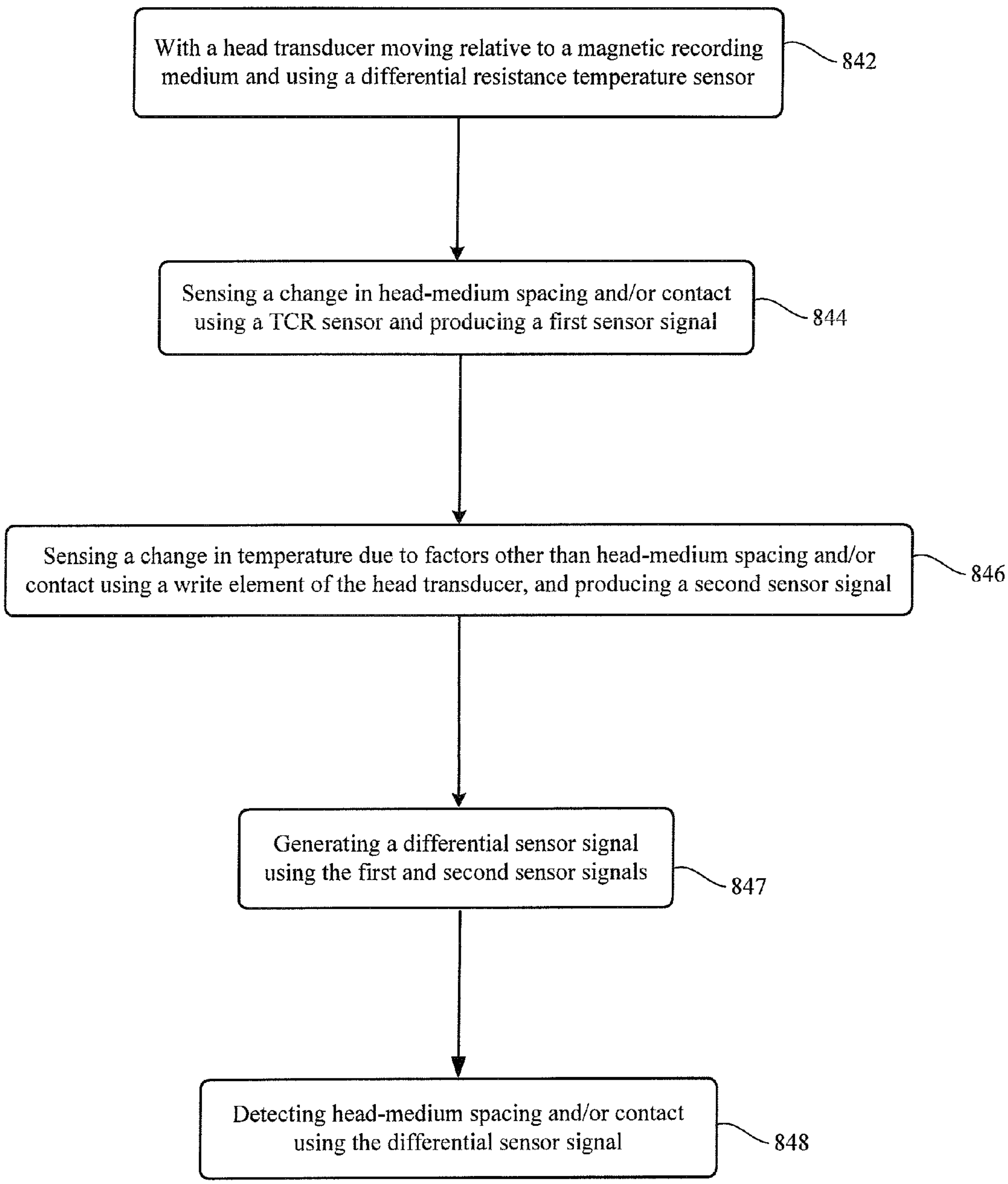

With a head transducer moving relative to a magnetic recording medium and using a differential resistance temperature sensor
832
Sensing a change in head-medium spacing and/or contact using a 1st TCR sensor and producing a first sensor signal
834
Sensing a change in temperature due to factors other than head-medium spacing and/or contact using a 2nd TCR sensor and producing a second sensor signal
836
Generating a differential sensor signal using the first and second sensor signals
837
Detecting head-medium spacing and/or contact using the differential sensor signal
838

Fig. 16B


With a head transducer moving relative to a magnetic recording medium and using a differential resistance temperature sensor
842
Sensing a change in head-medium spacing and/or contact using a TCR sensor and producing a first sensor signal
844
Sensing a change in temperature due to factors other than head-medium spacing and/or contact using a write element of the head transducer, and producing a second sensor signal
846
Generating a differential sensor signal using the first and second sensor signals
847
Detecting head-medium spacing and/or contact using the differential sensor signal
848

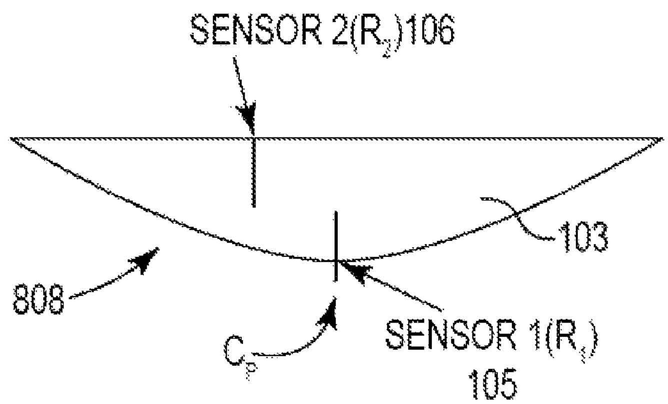


Fig. 17A

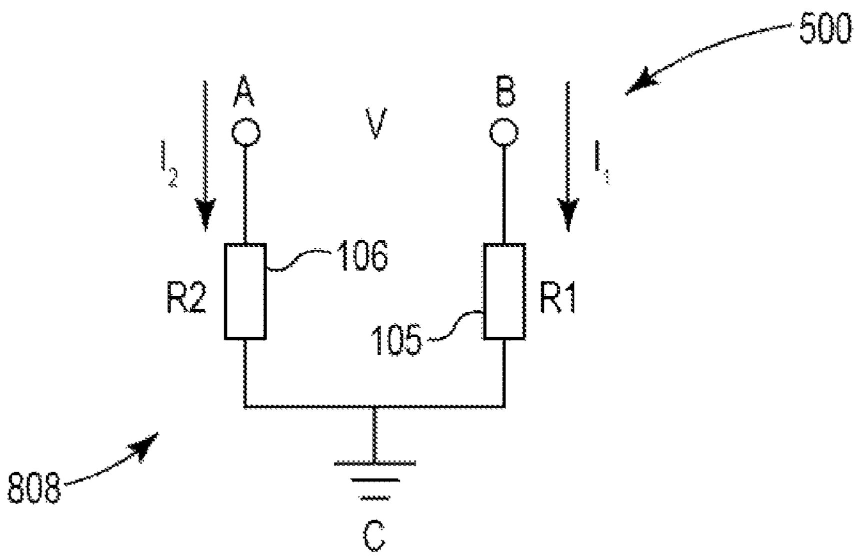


Fig. 17B

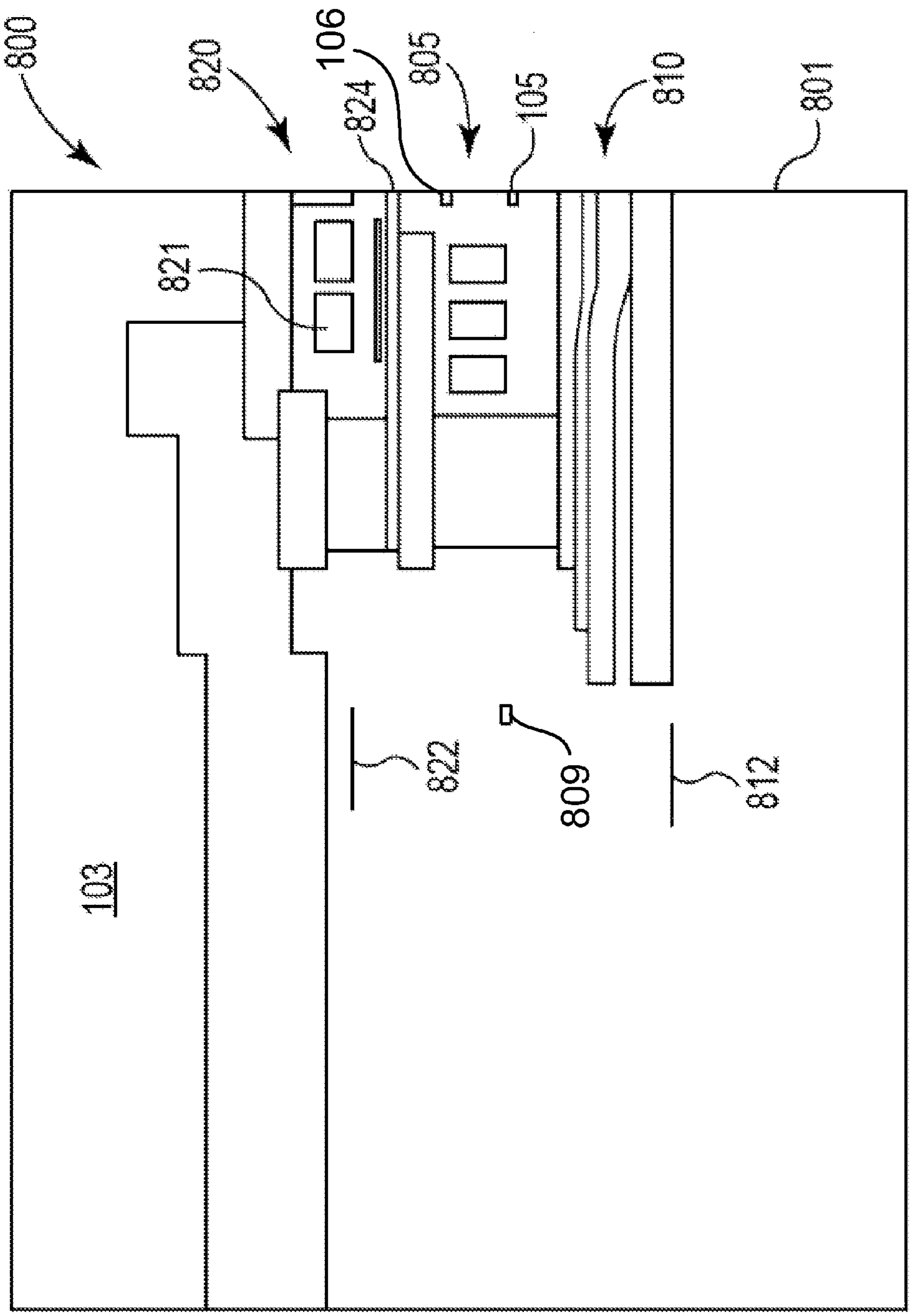


Fig. 17C

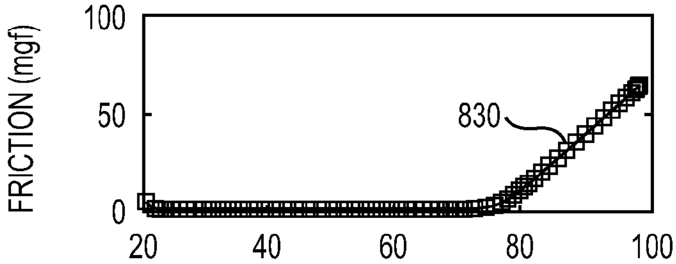


Fig. 18A

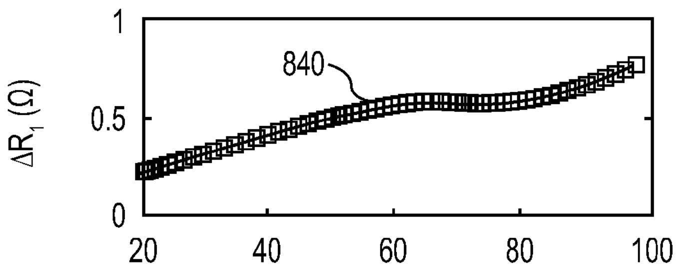


Fig. 18B

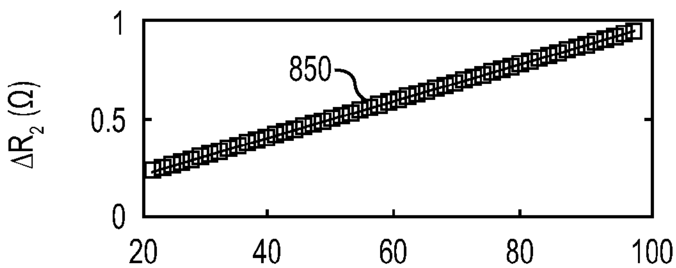


Fig. 18C

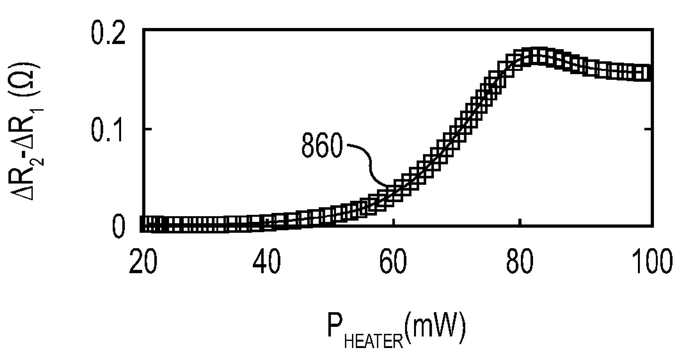
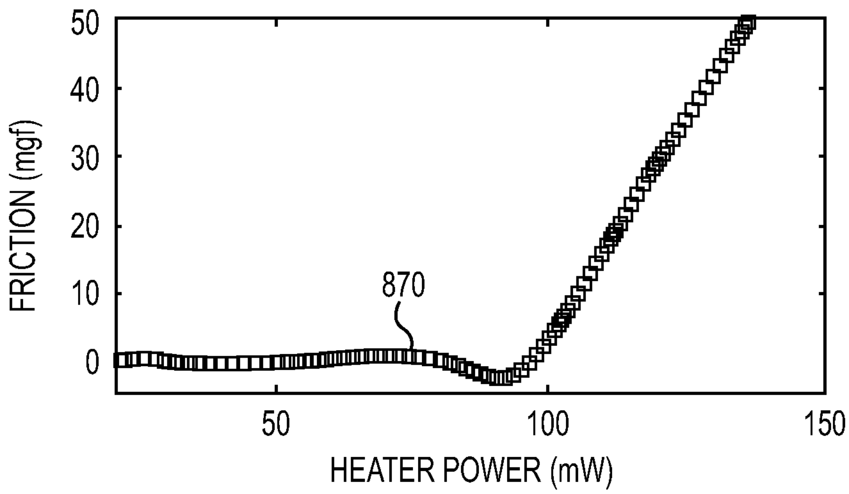
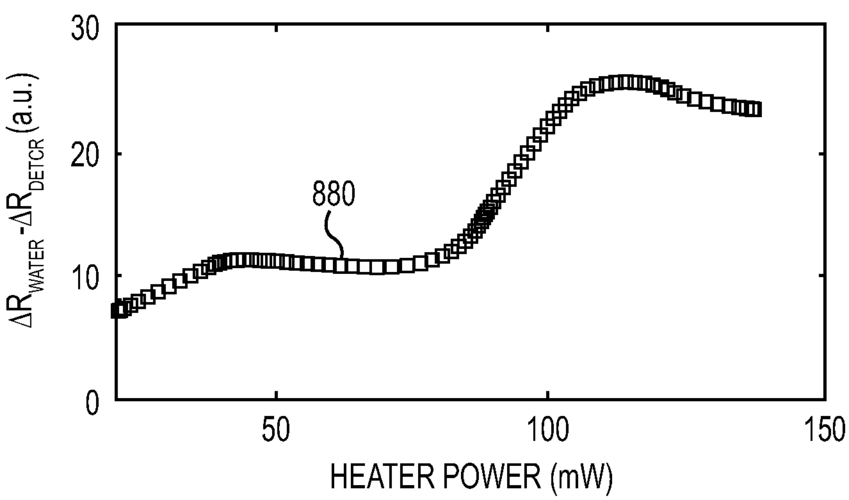


Fig. 18D



50
40
30
20
10
0
FRICTION (mgf)
870
50
100
150
HEATER POWER (mW)

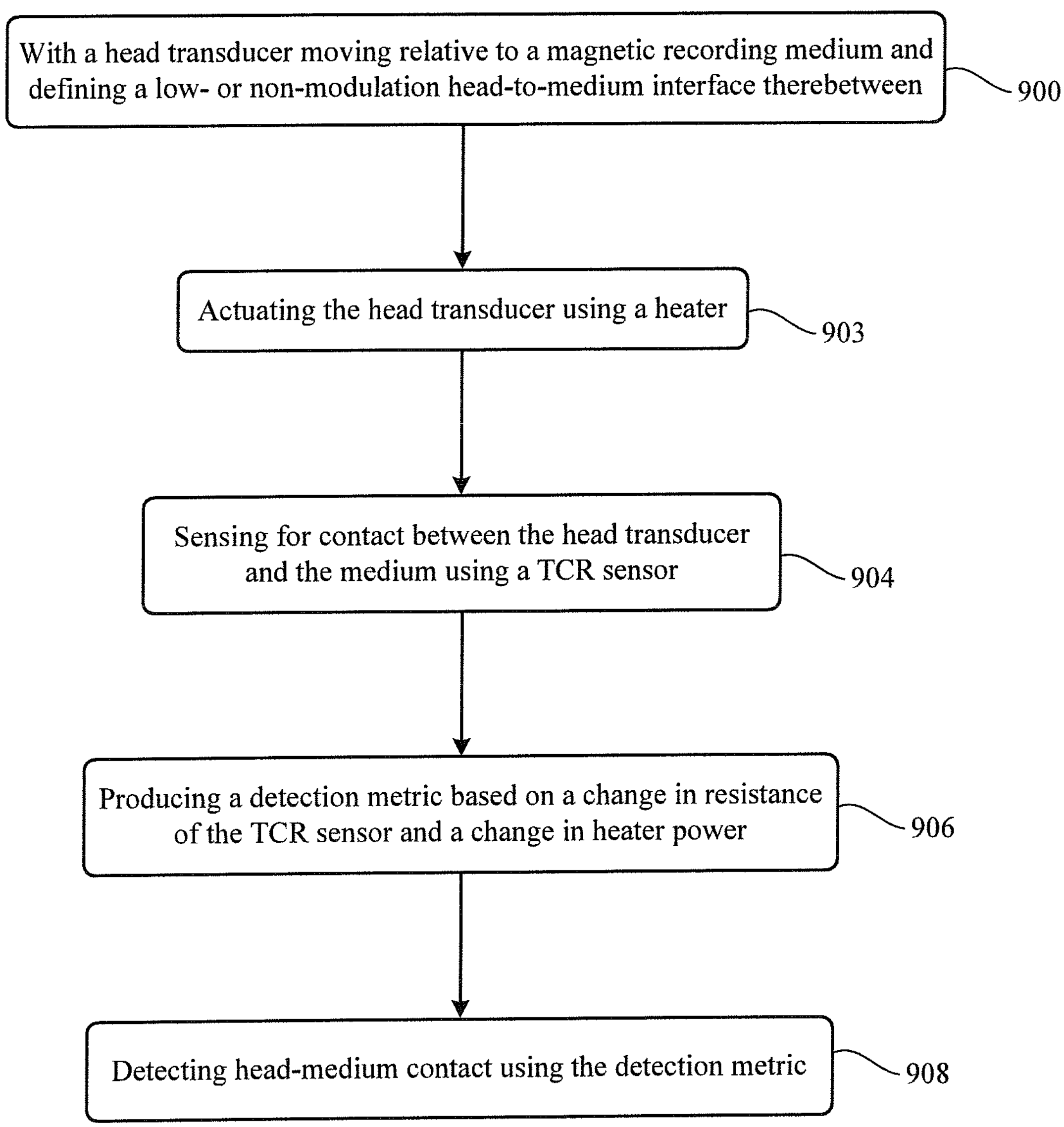
Fig. 19



30
20
10
0
$\Delta R_{WATER} - \Delta R_{DETCR}$ (a.u.)
880
50
100
150
HEATER POWER (mW)

Fig. 20

Fig. 21


With a head transducer moving relative to a magnetic recording medium and defining a low- or non-modulation head-to-medium interface therebetween
900
Actuating the head transducer using a heater
903
Sensing for contact between the head transducer and the medium using a TCR sensor
904
Producing a detection metric based on a change in resistance of the TCR sensor and a change in heater power
906
Detecting head-medium contact using the detection metric
908

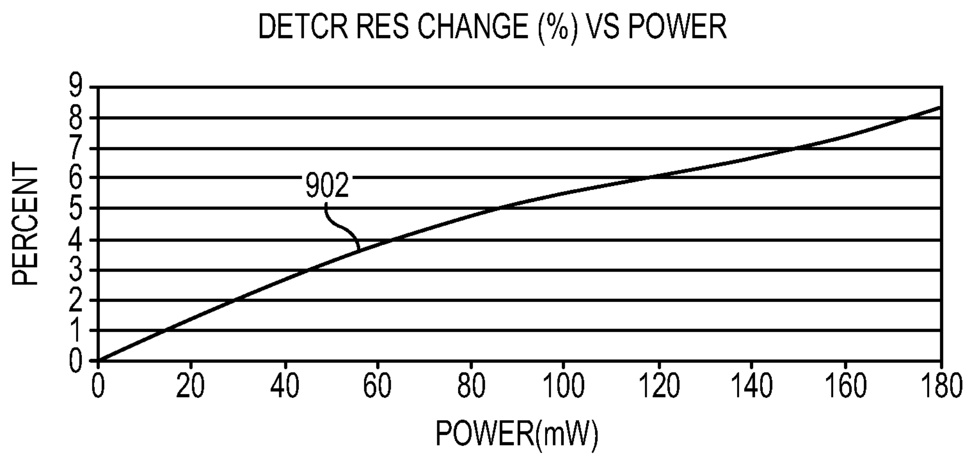


Fig. 22A

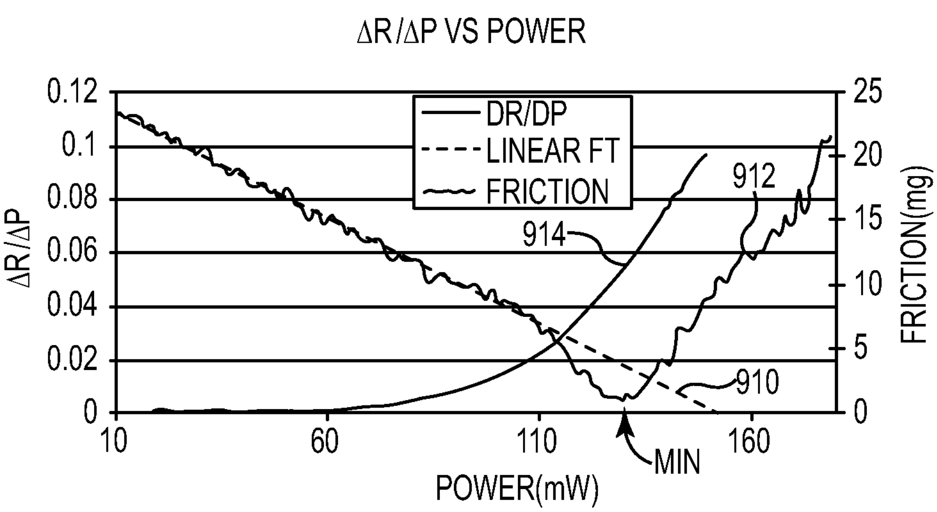


Fig. 22B

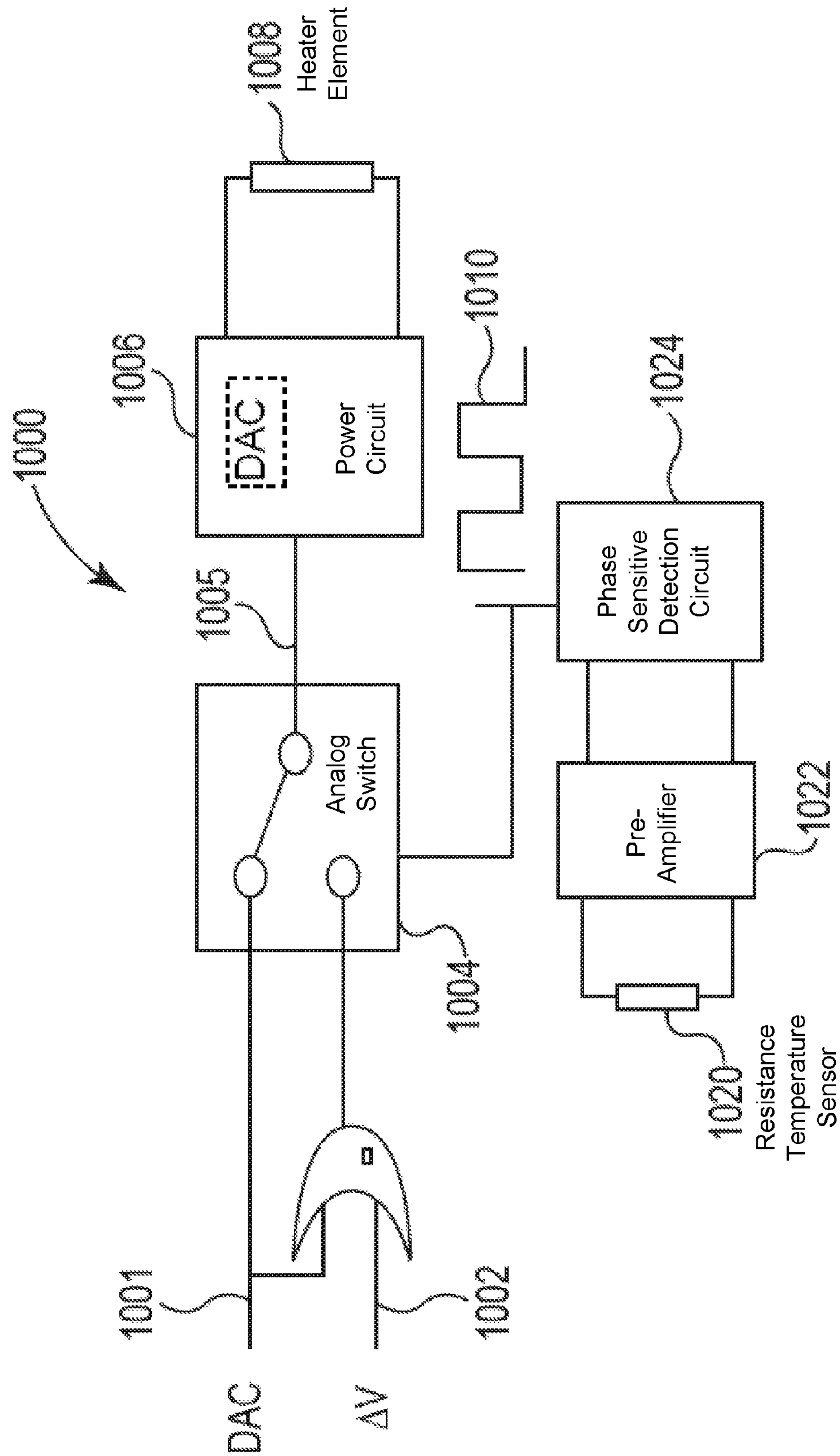

1000
1008
Heater Element
1006
DAC
Power Circuit
1010
1024
Phase Sensitive Detection Circuit
1005
Analog Switch
Pre-Amplifier
1022
1004
1020
Resistance Temperature Sensor
1001
1002
DAC
ΔV

Fig. 23

HEAD TRANSDUCER WITH MULTIPLE RESISTANCE TEMPERATURE SENSORS FOR HEAD-MEDIUM SPACING AND CONTACT DETECTION

RELATED PATENT DOCUMENTS

This application is a continuation of U.S. Ser. No. 14/457,694, filed Aug. 12, 2014, which is a continuation of U.S. Ser. No. 13/299,139 filed Nov. 17, 2011, now U.S. Pat. No. 8,810,952, which claims the benefit of Provisional Patent Application Ser. Nos. 61/414,733 and 61/414,734 both filed on Nov. 17, 2010, to which priority is claimed pursuant to 35 U.S.C. §119(e) and which are hereby incorporated herein by reference in their respective entirety.

SUMMARY

Embodiments of the disclosure are directed to an apparatus which includes a head transducer configured to interact with a magnetic recording medium, a first sensor having a temperature coefficient of resistance (TCR) and configured to produce a first sensor signal, and a second sensor having a TCR and configured to produce a second sensor signal. One of the first and second sensors is situated at or near a close point of the head transducer in relation to the magnetic recording medium, and the other of the first and second sensors spaced away from the close point. Circuitry is configured to combine the first and second sensor signals and produce a combined sensor signal indicative of one or both of a change in head-medium spacing and head-medium contact. The first sensor may include one of a positive TCR and a negative TCR, and the second sensor may include the other of the positive TCR and the negative TCR.

In accordance with other embodiments, the first and second sensor are arranged to define a differential resistance temperature sensor. Circuitry is configured to combine the first and second sensor signals to produce a differential signal indicative of one or both of the change in head-medium spacing and head-medium contact. A detector is configured to detect one or both of the head-medium spacing change and head-medium contact using the differential signal.

Various method embodiments involve sensing, with a head transducer moving relative to a magnetic recording medium, one or both of a change in head-medium spacing and head-medium contact using a first sensor having a coefficient of resistance (TCR). Methods also involve sensing a change in temperature due to factors other than head-medium spacing change and head-medium contact using a second sensor having a TCR. A first sensor signal is produced by the first sensor and a second sensor signal is produced by the second sensor. Methods further involve generating a combined sensor signal indicative of one or both of the change in head-medium spacing and head-medium contact using the first and second sensor signals, and detecting one or both of the change in head-medium spacing and head-medium contact using the combined sensor signal. In some embodiments, the first sensor comprises one of a positive TCR and a negative TCR, and the second sensor comprises the other of the positive TCR and the negative TCR. In other embodiments, the first and second sensor are arranged to define a differential resistance temperature sensor.

In accordance with various embodiments, an apparatus includes a head transducer configured to interact with a magnetic recording medium and a differential resistance temperature sensor supported by the head transducer. The differential resistance temperature sensor includes a first sensor having a temperature coefficient of resistance and situated at or near a close point of the head transducer in relation to the magnetic recording medium, and a write element of the head transducer spaced away from the first sensor. A detector is configured to detect one or both of a head-medium spacing change and head-medium contact using a differential signal generated by the differential resistance temperature sensor.

According to other embodiments, an apparatus includes a head transducer configured to interact with a magnetic recording medium, and a heater configured to actuate the head transducer. A sensor is situated at the head transducer and has a temperature coefficient of resistance. The sensor is configured to sense for contact between the head transducer and the medium. A detector is coupled to the sensor and the heater, and configured to detect head-medium contact using a detection metric based on a change in resistance of the sensor and a change in heater power. The detection metric may be based on a rate of change in resistance of the sensor and a rate of change in heater power. For example, the detection metric may be defined by a ratio $\Delta R/\Delta P$, where ΔR is a rate of change in resistance of the sensor and ΔP a rate of change in heater power. In some embodiments, the detector is configured to make a direct in situ measurement of $\Delta R/\Delta P$.

These and other features and aspects of various embodiments may be understood in view of the following detailed discussion and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a simplified side view of a heater-actuated head transducer arrangement which incorporates a TCR sensor in accordance with various embodiments;

FIG. **2** is a front view of the heater-actuated head transducer arrangement shown in FIG. **1**;

FIG. **3** shows the heater-actuated head transducer arrangement of FIGS. **1** and **2** in a pre-actuated configuration and an actuated configuration;

FIG. **4**A illustrates a representative temperature profile for a heater-actuated recording head transducer of the type shown in FIGS. **1-3** before, during, and after contact between the head transducer and a surface of a magnetic recording disk;

FIG. **4**B illustrates a representative temperature profile for a non-thermal actuatable recording head transducer before, during, and after contact between the head transducer and a surface of a magnetic recording disk;

FIGS. **5**A and **5**B are flow charts showing various processes of methods for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments;

FIGS. **6**A and **6**B are flow charts showing various processes of methods for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments;

FIG. **7** is a schematic illustration of a portion of a slider which supports a head transducer at a disk interface relative to a surface of a magnetic storage medium in accordance with various embodiments;

FIGS. **8** and **9** are graphs showing temperature rise as a function of heater power at the two TCR sensor locations depicted in FIG. **7**, respectively;

FIG. **10** is a diagram of an equivalent circuit depicting two TCR sensors arranged in series on a head transducer for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments;

FIG. **11** is a representative curve showing the voltage across electrical connection posts of the circuit of FIG. **10** as a function of heater element power with an apparent contact signature;

FIG. **12** shows a representative example of a layout of two TCR sensors in a recording head transducer in accordance with various embodiments;

FIG. **13** is a diagram of an equivalent circuit depicting two TCR sensors arranged on a head transducer in parallel for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments;

FIG. **14** is a representative curve showing the voltage across posts A and B of the equivalent circuit shown in FIG. **13** as a function of heater element power in accordance with various embodiments;

FIG. **15** shows a representative layout of a parallel-connected resistance temperature sensor in a recording head transducer according to various embodiments;

FIGS. **16**A and **16**B are flow charts showing various processes of methods for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments;

FIG. **17**A is an illustration of two TCR sensors arranged on a head transducer for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments;

FIG. **17**B is a diagram of an equivalent circuit depicting two TCR sensors arranged as a differential resistance temperature sensor in accordance with various embodiments;

FIG. **17**C is a cross-sectional illustration of a trailing section of a slider that supports a recording head transducer and resistance temperature sensor assembly in accordance with various embodiments;

FIGS. **18**A-**18**D are various graphs that demonstrate the efficacy of a resistance temperature sensor assembly that provides for improved signal-to-noise ratio of head-media contact detection and thermal asperity detection using differential resistance temperature sensors in accordance with various embodiments;

FIGS. **19** and **20** show plots of data from an experiment that demonstrate the efficacy of using a differential resistance temperature sensor assembly that comprises one resistance temperature sensor and a writer coil of the recording head transducer in accordance with various embodiments;

FIG. **21** is a flow chart showing various processes of a method for detecting head-medium contact for a low- or non-modulation head-to-medium interface in accordance with various embodiments;

FIG. **22**A is a plot of resistance temperature sensor resistance versus heater element power for a resistance temperature sensor configured to provide a non-modulation based metric for evaluating head-media spacing and performing head-media contact detection in accordance with various embodiments;

FIG. **22**B is a plot of a non-modulation based metric for evaluating head-media spacing and performing head-media contact detection in accordance with various embodiments; and

FIG. **23** is a circuit diagram of one approach for measuring a detection metric based on a rate of change in resistance of a TCR sensor and a rate of change in heater power in situ a hard disk drive in accordance with various embodiments.

DETAILED DESCRIPTION

Data storage systems commonly include one or more recording heads that read and write information to a recording medium. It is often desirable to have a relatively small distance or spacing between a recording head and its associated media. This distance or spacing is known as "fly height" or "head-media spacing." By reducing the head-media spacing, a recording head is typically better able to both write and read data to and from a medium. Reducing the head-media spacing also allows for surveying of recording medium topography, such as for detecting asperities and other features of the recording medium surface.

In accordance with various embodiments, and with reference to FIGS. **1-3**, a slider **100** is shown supported by a suspension **101** in close proximity to a rotating magnetic storage medium **160**. The slider **100** supports a recording head transducer **103** and a heater **102** thermally coupled to the head transducer **103**. The heater **102** may be a resistive heater that generates thermal heat as electrical current is passed through the heater **102**. The heater **102** is not limited to resistive heaters, and may include any type of heating source. The thermal energy generated by the heater **102** causes thermal expansion of the head transducer **103**. This thermal expansion can be used to reduce the head-media spacing **107** in a data storage system. It is noted that, in some embodiments, a non-thermal actuator can be used to reduce the head-media spacing **107**.

A TCR sensor **105** is shown situated on the head transducer **103** at the close point to the magnetic recording medium **160**. The close point is generally understood to be the closest point of contact between the head transducer **103** and the magnetic recording medium **160**. As discussed previously, actuation of the head transducer **103** can be realized by a thermal actuator, such as the heater **102**, or other actuator (e.g., a writer). Bias power is applied to the TCR sensor **105** to raise the surface temperature of the sensor **105** and adjacent portion of the head transducer **103** to be substantially higher than the temperature of the magnetic recording medium **160**.

The TCR sensor **105** is preferably configured to sense changes in heat flow for detecting asperities of the medium **160** and head-media contact. Details concerning head-media spacing and contact determinations in accordance with various embodiments of the disclosure are provided in commonly owned U.S. patent application Ser. No. 12/941,461 filed Nov. 8, 2010 which is incorporated herein by reference.

As is depicted in FIG. **3**, before head-media contact, there is an air gap **107** defined between the hot head surface and the relatively cool disk **160**. The head transducer **103**, air gap **107**, and magnetic recording disk **160** define one level of heat transfer rate. When the head transducer **103** is in contact with the disk **160**, such as after activation of the thermal actuator or heater **102**, the direct contact between the high thermal conductivity materials of the head transducer **103** and the disk **160** significantly increases the heat transfer rate. As such, the TCR sensor **105** on the head transducer **103** senses a drop of temperature or an excursion of temperature trajectory, allowing for detection of head-media contact.

FIG. **4**A illustrates a representative temperature profile for a recording head transducer **103** of the type shown in FIGS. **1-3** before, during, and after contact between the head transducer **103** and a surface of the magnetic recording disk **160**. In this illustrative example, the temperature profile is represented as a steady state DC signal. When the head transducer **103** is actuated by a thermal actuator **102**, the head transducer surface temperature will increase with the actuation due to the heat generated by the thermal actuator **102**. The head transducer temperature will be higher than the temperature of the disk **160**. As such, the disk **160** acts as a heat sink in this scenario.

When the head transducer **103** contacts the disk **160**, the head transducer surface temperature will drop due to a change in heat transfer rate resulting from the contact. The head transducer surface temperature will continue to increase due to thermal actuator heating and frictional heating. The change in temperature or excursion in temperature trajectory can be used to declare head-media contact.

FIG. **4**B illustrates a representative temperature profile for a recording head transducer **103** which is actuated by a non-thermal actuator. In this illustrative example, the TCR sensor **105** bias power self-heats the TCR sensor to a temperature substantially higher than the temperature of the disk **160**. The disk **160** acts as a heat sink in this scenario. When the head transducer **103** is actuated down toward the disk **160**, the heat transfer rate increases gradually, which causes a gradual temperature decrease in the TCR sensor temperature. When the head transducer **103** comes into contact with the disk **160**, there will be a change in heat transfer rate, causing a head transducer surface temperature excursion. The TCR sensor **105** on the head transducer surface measures this temperature excursion to detect head-media contact. Should further actuation into head-media contact occur, the temperature will eventually increase due to frictional heating.

Embodiments of the disclosure are directed to methods and apparatus for determining head-media spacing and detecting contact at the head-disk interface based on two resistive temperature sensors with different signs of temperature coefficient of resistance (TCR). Embodiments of the disclosure involve using multiple resistance temperature sensors with different signs of temperature coefficient of resistance located at different locations inside the slider, analyzing the output of the sensors, and using the output to provide feedback of the drive operation condition.

Head-media contact detection and/or head-media spacing sensing technologies are critical for the performance and reliability of hard disk drives. Higher contact detection repeatability enables lower active clearance, and thus higher recording density. Higher contact detection sensitivity reduces wear and improves reliability. Embodiments of the disclosure provide for head-media contact detection and spacing sensing using two sensors, one with a positive TCR, the other with negative TCR, which advantageously eliminates the requirement of any extra electrical connection pads.

In accordance with various embodiments, methods involve detecting head-media contact using two resistance temperature sensors, one with a positive TCR, the other with a negative TCR. These sensors are preferably embedded in different locations in the slider. For example, one sensor can be located near the close point so that its response is sensitive to change in head-media spacing, head-to-disk contact, and other events such as heater-induced temperature rise and/or environmental temperature fluctuations. The other sensor can be located away from the close point so that its response is only sensitive to events such as heater-induced temperature rise and/or environmental temperature fluctuations.

Because the two sensors have different signs of TCR, the combined output of the two sensors with specific combination of resistance and TCR values will only contain the head-media spacing and/or head-to-disk contact contributions. Thus, the combined output can be used to sense head-media spacing change and/or contact events without the requirement of an extra electrical connection pad. The fact that this technique does not require extra electrical connection pads is significant for simplicity of the head design, reduction of cost, and improvement in reliability.

FIG. **5**A is a flow chart showing various processes of a method for detecting head-media contact and/or head-media spacing changes in accordance with embodiments of the disclosure. With a head transducer comprising a slider moving **140** relative to a magnetic recording medium, a method involves sensing **142** a change in a change in head-medium spacing and/or head-medium contact using a first TCR sensor, and producing a first sensor signal. The method also involves sensing **144** a change in temperature due to factors other than head-medium spacing and/or head-medium contact using a second TCR sensor, and producing a second sensor signal. The method shown in FIG. **5**A further involves generating **146** a combined sensor signal indicative of head-medium spacing and/or head-medium contact, and detecting **148** head-medium spacing and/or head-medium contact using the combined sensor signal.

FIG. **5**B is a flow chart showing various processes of a method for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments. With a head transducer comprising a slider moving **180** relative to a magnetic recording medium, a method involves producing **182** a first sensor signal indicative of a thermal boundary condition at a close point of the head transducer relative to the medium using a first TCR sensor. The method also involves producing a second sensor signal indicative of temperature change due to factors other than those influenced by the thermal boundary condition using a second TCR sensor. The method further involves generating **186** a combined sensor signal indicative of head-medium spacing and/or head-medium contact, and detecting **188** head-medium spacing and/or head-medium contact using the combined sensor signal.

FIG. **6**A is a flow chart showing various processes of a method for detecting head-media contact and/or head-media spacing changes in accordance with embodiments of the disclosure. With a head transducer comprising a slider moving **202** relative to a magnetic recording medium, changes in temperature indicative of head-medium spacing changes are sensed **204** using a first TCR sensor. The first TCR sensor is supported by the head transducer and is connected **206** via a fixed number of electrical connection pads (e.g., 2). The method also involves sensing **208** temperature changes due to factors other than head-medium spacing changes and contact using a second TCR sensor also connected **210** via a fixed number of electrical connection pads (e.g., 2). The first and second TCR sensors have different signs of TCR, one positive and the other negative. The method further involves combining **212** signals output by the first and second TCR sensors to produce a combined output signal indicative of head-medium spacing change and/or head-medium contact. Head-medium spacing changes and/or head-medium contact is measured **216** using the combined output signal. Notably, making temperature-based head-medium contact and head-medium spacing change measurements is achieved without addition **214** of an extra electrical connection pad.

FIG. **6**B is a flow chart showing various processes of a method for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments. With a head transducer comprising a slider moving **302** relative to a magnetic recording medium, the method involves preferentially sensing **304** temperature changes at a thermal boundary at a close point of the head transducer using a first TCR sensor having a fixed number of electrode connection pads. The method also involves preferentially sensing **306** temperature changes other than at the thermal boundary using a second TCR sensor having a fixed number of electrode connection pads and a TCR with a sign different from that of the first TCR sensor. Signals output by the first and second sensors are used to produce **308** a combined output signal indicative of head-medium spacing change and/or head-medium contact. As in the embodiments illustrated in FIG. **6**A above, making temperature-based head-medium contact and head-medium spacing change measurements **312** is achieved without addition **310** of an extra electrical connection pad.

FIG. **7** is a schematic illustration of a portion of a slider **100**, which supports a head transducer **103** at a disk interface relative to a surface of a magnetic storage medium **160** in accordance with embodiments of the disclosure. The schematic illustration shown in FIG. **7** can define, for example, a disk interface in a magnetic recording hard drive. In FIG. **7**, it is assumed that the disk is spinning at a high RPM and a recording head **103** is flying several nanometers away from the surface of the disk **160** with the spacing controlled by the air bearing. To further bring the head **103** closer to the surface of the disk **160**, a heater element **102** embedded in the head **103** is actuated to create thermal expansion in the head **103** and reduce the head-medium spacing.

The heat generated by the heater element **102** and/or the writer coil creates a temperature rise in the head transducer **103**. Before contact, the heat is mainly conducted away from the head transducer **103** through an air gap **107** between the disk **160** and the transducer head **103** and into the disk **160**. The thermal conductance of the air gap **107** increases as the head-medium spacing decreases and the air pressure increases. When the head transducer **103** contacts the disk **160**, the thermal conductance increases dramatically. After the head transducer **103** contacts the disk **160**, the resulting frictional heating will generate an extra heat source. The combined effect of different thermal energy transfer mechanisms, such as heater element heating, writer coil heating, air bearing cooling, disk cooling, and frictional heating, for example, results in a characteristic temperature rise at different locations in the head transducer **103** as a function of heater element power, writer current, clearance, and/or contact events. By measuring the temperature as a function of heater power, head-media spacing and/or contact events can be monitored.

In accordance with various embodiments, and with continued reference to FIG. **7**, one TCR sensor, R_1 (**105**), is located near the close point, and the other TCR sensor, R_2 (**106**), is located away from the close point. Situating the TCR sensor R_1 (**105**) at or near the close point provides for preferential sensing of temperature/temperature changes generated at a thermal boundary at the close point of the head transducer **103**. Situating TCR sensor R_2 (**106**) away from the close point (e.g., elsewhere on the head transducer **103**/slider **100**) provides for preferential sensing of temperature/temperature changes generated from thermal sources other than that at or near the close point. Representative examples of temperature rise at the two TCR sensor locations depicted in FIG. **7** are illustrated in FIGS. **8** and **9**, respectively.

The temperature rise, ΔT_1, of TCR sensor R_1 (**105**) is shown in temperature curve **402** plotted as a function of heater element power, P_{heater}. As can be seen in FIG. **8**, the temperature rise of TCR sensor R_1 (**105**) increases as a function of heater element power over the entire heater element power range. The rate of increase slows down gradually when the heater element power is increased from 20 mW to 80 mW due to the increase in thermal conductance of the air gap **107**. The temperature curve **402** shows a shoulder **403** between 80 mW and 100 mW (beginning at a location on the temperature curve **402** indicated by arrow **401**) because of further increase in cooling due to proximity and/or contact effect. After 100 mW, the rate of temperature rise increases slightly due to frictional heating.

The temperature rise, ΔT_2, of TCR sensor R_2 (**106**) is shown in FIG. **9** also increase as a function of heater element power, but does not have the shoulder (**403** shown in FIG. **8**) because the TCR sensor R_2 (**106**) is less sensitive to the thermal boundary condition at the close point. It is understood that the temperature curves shown in FIGS. **8** and **9** are provided only for demonstrational purposes. Since temperature distribution in the head transducer **103** can be obtained from a thermomechanical model accurately, locations of the two TCR sensors R_1 (**105**) and R_2 (**106**) can be determined and optimized.

The temperature changes ΔT_1 and ΔT_2 of TCR sensors R_1 (**105**) and R_2 (**106**) produces change in the resistance of these TCR sensors, which can be characterized as follows:

$$R_i=R_{i,0}+R_{i,0}\alpha_i\Delta T_i \quad (1)$$

where α_i is the temperature coefficient of resistance of the TCR sensor R_1 (**105**), and $R_{i,o}$ is the resistance at ambient temperature of TCR sensor R_1 (**105**). By choosing sensor materials with different signs of TCR and combining them in serial or parallel, contact detection signals can be produced without the addition of extra electrical connection pads.

FIG. **10** is a diagram of an equivalent circuit **500** depicting two TCR sensors R_1 (**105**) and R_2 (**106**) arranged on a head transducer for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments. In accordance with the representative embodiment shown in FIG. **10**, the two TCR sensors R_1 (**105**) and R_2 (**106**) with different signs of temperature coefficient of resistance (i.e., one positive and the other negative) are connected in series. Given a current I, the voltage drop across the two TCR sensors R_1 (**105**) and R_2 (**106**) is given by:

$$V=I(R_1+R_2)=I(R_{1,0}+R_{1,0}\alpha_1\Delta T_1+R_{2,0}+R_{2,0}\alpha_2\Delta T_2) \quad (2)$$

where ΔT_1 and ΔT_1 are the temperature changes of the TCR sensors R_1 (**105**) and R_2 (**106**), respectively, α_1 and α_2 are the temperature coefficients of resistance of the TCR sensors R_1 (**105**) and R_2 (**106**), respectively, and $R_{1,0}$ and $R_{2,0}$ are the resistances at ambient temperature of the TCR sensors R_1 (**105**) and R_2 (**106**).

By choosing the proper combinations of $R_{1,0}$, α_1, $R_{2,0}$, and α_2, so that

$$R_{1,0}\alpha_1\Delta T_1+R_{2,0}\alpha_2\Delta T_2=\text{constant} \quad (3)$$

for all heater element power levels before contact, i.e., for heater element power smaller than 60 mW in the illustrative example shown in FIGS. **8** and **9**, the resistance change created by the change in the thermal boundary condition near the close point can be amplified. FIG. **11** is a representative curve **510** showing the voltage, V, across posts A and B of the circuit **500** of FIG. **10** as a function of heater element power, P_{heater}, with an apparent contact signature. The sudden change in the voltage curve **510** beginning around 80 mV represents onset of head-media contact.

FIG. **12** shows a representative example of the layout **600** of the TCR sensors R_1 (**105**) and R_2 (**106**) in a recording head transducer **103** in accordance with various embodiments. In the layout **600** shown in FIG. **12**, the TCR sensor R_1 (**105**) is located at the close point, P_C, and the TCR sensor R_2 (**106**) sensor is located away from the close point, C_P. The two TCR sensors R_1 (**105**) and R_2 (**106**) are connected in series in this illustrative embodiment between electrical connection pads or posts **602** (Post A) and **606** (Post B) via leads **614** and **610**. Leads **604** and **608** are shown connected to electrical connection pads **602** and **606**, respectively. The layout **600** illustrated in FIG. **12** shows that TCR sensors R_1 (**105**) and R_2 (**106**) can be incorporated into a recording head transducer using existing leads and without the addition of an extra electrical connection pad.

In accordance with another embodiment, and as shown in the equivalent circuit **700** illustrated in FIG. **13**, the two TCR sensors R_1 (**105**) and R_2 (**106**) with different signs of temperature coefficient of resistance (i.e., one positive and the other negative) are connected in parallel. The voltage drop across the combination TCR sensors R_1 (**105**) and R_2 (**106**) is given by:

$$V=IR=I(R_{1,0}+R_{1,0}\alpha_1\Delta T_1)(R_{2,0}+R_{2,0}\alpha_2\Delta T_2)/(R_{1,0}+R_{1,0}\alpha_1\Delta T_1+R_{2,0}+R_{2,0}\alpha_2\Delta T_2) \quad (4)$$

By choosing a combination of $R_{1,0}$, α_1, $R_{2,0}$, and α_2, so that

$$\alpha_1\Delta T_1+\alpha_2\Delta T_2+\alpha_1\Delta T_1\alpha_2\Delta T_2=\text{constant} \quad (5)$$

and

$$R_{1,0}\alpha_1\Delta T_1+R_{2,0}\alpha_2\Delta T_2=\text{constant} \quad (6)$$

for all heater element power levels before contact, i.e., for heater element power smaller than 60 mW in the illustrative example shown in FIGS. **13** and **14**, the resistance change created by the change in the thermal boundary condition near the close point can also be amplified. The condition defined by Equation (5) above can be released by omitting the higher order term $\alpha_1\Delta T_1\alpha_2\Delta T_2$, because the TCR of most materials is much smaller than 1.

FIG. **14** is a representative curve **720** showing the voltage, V, across posts A and B of the circuit **700** of FIG. **13** as a function of heater element power, P_{heater}. In this representative example, $R_{1,0}\approx R_{2,0}$ and $\alpha_1\approx\alpha_2$.

FIG. **15** shows a representative layout **750** of a parallel-connected resistance temperature sensor in a recording head transducer according to various embodiments. In the layout **750** shown in FIG. **15**, the TCR sensors R_1 (**105**) and R_2 (**106**) are connected in parallel, with the TCR sensor R_1 (**105**) located at the close point, P_C, and the TCR sensor R_2 (**106**) sensor located away from the close point, C_P. The two TCR sensors R_1 (**105**) and R_2 (**106**) are connected in parallel in this illustrative embodiment between electrical connection pads or posts **752** (Post A) and **756** (Post B) via leads **764** and **760**. Leads **754** and **758** are shown connected to electrical connection pads **752** and **756**, respectively. The layout **750** illustrated in FIG. **15** shows that TCR sensors R_1 (**105**) and R_2 (**106**) can be incorporated into a recording head transducer using existing leads and without the addition of an extra electrical connection pad. It is noted that a series-connected resistance temperature sensor arrangement preforms appreciably better than a parallel-connected resistance temperature sensor arrangement.

Various materials with a positive temperature coefficient of resistance that can be used in the construction of a TCR sensor according to embodiments of the disclosure include, but are not limited to, Cr, FeNi alloy, Ni, and W, among others. Various materials with a negative temperature coefficient of resistance that can be used in the construction of a TCR sensor according to embodiments of the disclosure include, but are not limited to, TaN, VO, and VO_2, among others.

Embodiments of the disclosure are directed to resistance temperature sensor assemblies that provide for enhanced signal-to-noise ratios (SNRs) due to calibrating out head transducer temperature variation. Embodiments of the disclosure are directed to resistance temperature sensor assemblies that have enhanced SNRs due to calibrating out head transducer temperature variation using existing head transducer electrical elements. For example, various embodiments employ a differential resistance temperature sensor assembly comprising a resistance temperature sensor and a writer coil of the recording head transducer, such as a writer coil for a BCR (Beyond Contact Recording) head. A BCR transducer head has a smaller airbearing feature to produce higher concentrated air pressure at the trailing edge in comparison to conventional transducer heads. A BCR transducer head has low contact modulation.

FIGS. **16**A and **16**B are flow charts showing various processes of methods for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments. According to FIG. **16**A, method embodiments involve a head transducer moving relative to a magnetic recording medium and use of a differential resistance temperature sensor **832**. The method illustrated in FIG. **16**A involves sensing **834** a change in head-medium spacing and/or head-medium contact using a first TCR sensor, and producing a first sensor signal. The method also involves sensing **836** a change in temperature due to factors other than head-medium spacing and/or head-medium contact using a second TCR sensor, and producing a second sensor signal. The method shown in FIG. **16**A further involves generating **837** a differential sensor signal using the first and second sensor signals, and detecting **838** head-medium spacing and/or head-medium contact using the differential sensor signal.

In accordance with FIG. **16**B, method embodiments involve a head transducer moving relative to a magnetic recording medium and use of a differential resistance temperature sensor **842**. The method illustrated in FIG. **16**B involves sensing **844** a change in head-medium spacing and/or head-medium contact using a TCR sensor, and producing a first sensor signal. The method also involves sensing **846** a change in temperature due to factors other than head-medium spacing and/or head-medium contact using a write element of the head transducer, and producing a second sensor signal. The method shown in FIG. **16**B further involves generating **847** a differential sensor signal using the first and second sensor signals, and detecting **848** head-medium spacing and/or head-medium contact using the differential sensor signal.

According to various embodiments, and with reference to FIGS. **17**A-**17**C, a resistance temperature sensor assembly **808** provides for improved SNR of head-media contact detection and thermal asperity detection using differential resistance temperature sensors. FIG. **17**A is an illustration of two TCR sensors R_1 (**105**) and R_2 (**106**) arranged on a head transducer **103** for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments. More particularly, the two TCR sensors R_1 (**105**) and R_2 (**106**) shown in FIG. **17**A are preferably arranged as a differential resistance temperature sensor assembly **808** on a head transducer **103** for detecting head-media contact and/or head-media spacing changes in accordance with various embodiments.

In FIG. **17**A, a TCR sensor R_1 (**105**) is located near the close point, C_P, of the head transducer **103** and a second TCR sensor R_2 (**106**) is located away from the close point, C_P. As discussed previously, situating the TCR sensor R_1 (**105**) at or near the close point, C_P, provides for preferential sensing of temperature/temperature changes generated at a thermal boundary at the close point, C_P, whereas situating the TCR sensor R_2 (**106**) away from the close point provides for preferential sensing of temperature/temperature changes generated from thermal sources other than that at or near the close point, C_P.

FIG. **17**B is a diagram of an equivalent circuit **850** depicting the two TCR sensors R_1 (**105**) and R_2 (**106**) arranged as a differential resistance temperature sensor assembly **808**. In the representative embodiment shown in FIG. **17**B, the two

TCR sensors R_1 (**105**) and R_2 (**106**) preferably have the same signs of temperature coefficient of resistance (i.e., either both positive or both negative). In some embodiments, the differential resistance temperature sensor assembly **808** shown **17**B may have a center tap that is a live terminal, instead of being coupled to ground.

The differential resistance temperature sensor assembly **808** provides for sensing of the difference in thermal boundary condition at the close point, C_P, (as measured using TCR sensor R_1 (**105**)) and at a location away from the close point, C_P (as measured using TCR sensor R_2 (**106**). The differential signal produced by the differential resistance temperature sensor assembly **808** illustrated in FIGS. **17**A-**17**C improves the contact detection SNR by removing the background created by the heater element and environment. It is noted that the common mode noise should be canceled prior to differential signal amplification.

Experiments were conducted to demonstrate the efficacy of the differential resistance temperature sensor assembly **808**. In one experiment, and with reference to FIGS. **18**A-**18**D, the resistance of one resistance temperature sensor, R_2 (e.g., TCR sensor R_2 (**106**)) located away from the close point, C_P, varies linearly with heater element power. The linear resistance response of the sensor R_2 can be seen in FIG. **18**C. The resistance of the other resistance temperature sensor, R_1 (e.g., TCR sensor R_1 (**105**) located at the close point, C_P, varies non-linearly with heater element power. The non-linear resistance response of the sensor R_1 can be seen in the plot of FIG. **18**B. The differential signal generated using outputs from sensors R_1 and R_2 is shown in the plot of FIG. **18**C, which clearly shows a head-media contact signature. It can be seen that if a head-media contact event is declared at 80 mW, then the friction force is relatively low (e.g. ~10 mgf), as can be seen in the plot of FIG. **18**A.

In accordance with some embodiments, and with continued reference to FIG. **17**A-**17**C, a differential resistance temperature sensor assembly **808** comprises one resistance temperature sensor and another component of the head transducer that includes TCR material, such as a writer coil, a reader or an inactive heater of the head transducer (e.g., a BCR head transducer). The resistance temperature sensor, such as TCR sensor R_1 (**105**), is located at the close point, C_P, and the writer coil, reader or unused heater (represented by sensor R_2 (**106**)) is situated at a typical location away from the close point, C_P.

In an experiment that demonstrated the efficacy of this differential resistance temperature sensor configuration, the heater element of the resistance temperature sensor was modulated at 180 Hz and a lock-in amplifier was used to read the difference of the voltage drop across the resistance temperature sensor and the writer coil. The resistance temperature sensor was biased at 164 μA and the writer coil was biased at 1 μA to make sure the differential response was flat before head-media contact (i.e., flat for heater element power between 50 mW and 80 mW in this example). FIGS. **19** and **20** show plots of data from the experiment that demonstrate the efficacy of using a differential resistance temperature sensor assembly that comprises one resistance temperature sensor and a writer coil of the recording head transducer. The curve **880** in FIG. **20** is the difference in voltage drop change between the resistance temperature sensor and the writer coil as a function of heater element power. The curve **870** in FIG. **19** is the friction force curve measured simultaneously. Embodiments of a differential resistance temperature sensor arrangement that comprises a resistance temperature sensor and a writer coil of the recording head transducer advantageously provides for improved head-media contact detection SNR without need for adding any extra structure or pads.

FIG. **17**C is a cross-sectional illustration of a trailing section of a slider **800** that supports a recording head transducer and resistance temperature sensor assembly in accordance with various embodiments. In FIG. **17**C, the slider **800** includes an airbearing surface **801** that faces a surface of an adjacent magnetic recording medium (not shown). The slider **800** supports a recording head transducer **805** which includes a reader **810** and a writer **820**. A heater **812** for the reader **810** can be actuated to cause the reader **810** to protrude toward the surface of the recording medium, thereby reducing the separation therebetween during read operations. The writer **820** includes a write pole **824** which is inductively coupled to one or more sets of coils **821**. A heater **822** for the writer **820** can be actuated to cause the writer **820** to protrude toward the surface of the recording medium, thereby reducing the separation therebetween during write operations.

In the illustration of FIG. **17**C, three resistive components are shown. Resistive components **105** and **106** are located on the ABS **801** and resistive component **809** is located away from the ABS **801**. Although these three resistive components are shown in FIG. **17**C, not all three are required, but are included for explanation of various embodiments. According to some embodiments, resistive components **105** and **106** are TCR sensors, and reference resistor **809** would not be present. In this scenario, when the heater **812** of the reader **810** is being used, TCR sensor **105** is closer to the close point than TCR sensor **106**. As a result, TCR sensor **105** is active and TCR sensor **106** is more distant from the close point and functions as the reference. When the heater **822** of the writer **820** is being used, TCR sensor **106** is closer to the close point than TCR sensor **105**, and is active during use of the writer heater **822**. In this case, TCR sensor **105** is more distant from the close point and functions as the reference.

According to embodiment involving use of reference resistor **809** positioned away from the ABS, only one ABS TCR sensor would be present. In the configuration shown in FIG. **17**C, TCR sensor **105** would preferably be present (and TCR sensor **106** would not be present) since TCR sensor **105** is coplanar with reference resistor **809** in the schematic illustration and could be formed in the same deposition and etch step, meaning that TCR sensor **105** is the more practical of the two TCR sensors **105** and **106**.

Various embodiments described herein involve contact detection based on a cooling event, where the medium is cooler than the head transducer. This is generally applicable for higher TCR sensor bias values and conducting media substrates, making the TCR sensor hotter than the medium. According to other embodiments, the head transducer surface temperature at the interface can be lowered to be substantially lower than the media temperature by lowering the bias power to the TCR sensor and, if desired, using a non-thermal actuator in the head transducer. This approach provides for improved frictional heating detection, which can be used to declare head-media contact. Such an approach is particularly useful for poorly conducting media substrates, such as glass.

Conventional approaches for detecting head-media contact often involve measuring an AC signal from a resistance temperature sensor that is believed to be caused by head modulation. The DC signal is filtered out because it is not believed to have a signal-to-noise ratio sufficient to detect a head-media contact event. For most, if not all, current advanced air bearing (ΔAB) implementations, this conventional approach has proved to be effective in detecting head-media contact.

However, great effort is currently being expended on developing an interface for contact or beyond contact recording

(BCR) to satisfy ever decreasing head-media spacing targets for achieving higher area densities. A key feature of these interfaces is very minimal modulation at head-media contact. Such a head-disk interface poses a great challenge to current contact detection methodologies, including those that employ a resistance temperature sensor. Because resistance temperature sensors are currently used on heads for thermal asperity detection, it would be highly desirable for next generation drives to adapt existing heads equipped with resistance temperature sensors for use in low modulation interfaces.

Various embodiments of the disclosure are directed to non-modulation based head-media contact detection apparatuses and methods. Head-media contact detection according to various embodiments is evaluated based on changes in a relationship of resistance and power associated with a resistance temperature sensor, rather than detecting air bearing-based or head-based modulation.

A resistance temperature sensor has been found to be a particularly useful head-media contact detection sensor for reasons discussed previously. A resistance temperature sensor is, in essence, a thermal sensitive resistor on a pole tip. A resistance temperature sensor measures the temperature change induced by all thermal condition changes from air pressure, clearance, and contact, among other changes.

FIG. **21** is a flow chart showing various processes of a method for detecting head-medium contact for a low- or non-modulation head-to-medium interface in accordance with various embodiments. With a head transducer moving relative to a magnetic recording medium and defining a low- or non-modulation head-to-medium interface therebetween **900**, method embodiments involve actuating **903** the head transducer using a heater, and sensing **904** for contact between the head transducer and the medium using a TCR sensor. The method also involves producing **906** a detection metric based on a change in resistance of the TCR sensor and a change in heater power, and detecting **908** head-medium contact using the detection metric.

According to various representative embodiments, the ratio of a change in resistance (ΔR) to a change in power (ΔP), denoted $\Delta R/\Delta P$, provides a non-modulation based metric for evaluating head-media spacing and performing head-media contact detection. The metric $\Delta R/\Delta P$ decreases linearly with decreasing head-to media clearance. Detecting a deviation from linearity in $\Delta R/\Delta P$ and a minima indicates head-media contact and head-media caused cooling and frictional heating. Such an approach does not rely on AAB modulation for contact detection. Experimentation has demonstrated that head-media spacing and contact detection in accordance with embodiments of the disclosure is very effective for implementations that use advanced air bearings and beyond contact recording AABs.

For an airbearing, head transducer cooling efficiency improves with reduced clearance due to an increase in thermal transport efficiency. Head transducer cooling efficiency reaches a maximum when the head transducer contacts the media because the media provides an efficient thermal sink to the head transducer. According to embodiments of the disclosure, head-media contact can be detected by monitoring the interface cooling efficiency that is not caused by head modulation.

The DC signal from a resistance temperature sensor is dominated by heater element-based heating. The resistance change caused by interface cooling/heating represents only a fraction of that caused by the heater element of the resistance temperature sensor. It is generally difficult to know with certainty where head-media contact occurs based on a resistance measurement, as can be seen in the plot shown in FIG. **22**A. FIG. **22**A is a plot **902** of resistance temperature sensor resistance versus heater element power.

One measure of the head-to-disk interface (HDI) cooling condition is the rate of the temperature rise over heater power, or $\Delta R/\Delta P$. $\Delta R/\Delta P$ decreases with a better cooling condition. $\Delta R/\Delta P$ reaches a minimum at head-media contact. $\Delta R/\Delta P$ will increase again after head-media contact due to frictional heating. The head-media contact can be detected by monitoring the metric $\Delta R/\Delta P$ instead of the head modulation.

An experiment was conducted to verify the efficacy of using $\Delta R/\Delta P$ for head-media contact detection. The experiment involved use of a BCR AAB head which incorporated a resistance temperature sensor. The resistance temperature sensor was biased with a fixed current from a source meter. The sensor resistance was measured by the same meter. The heater element power was applied with a voltage sourced from a second source meter. The power was measured with the same meter at the same time. Arm electronics RMS was taken at the same time as the resistance temperature sensor measurements.

A plot of the metric $\Delta R/\Delta P$ for the experiment is shown in FIG. **22**B. It can be seen in FIG. **22**B that the value of $\Delta R/\Delta P$ (plot **912**) is linearly trending down until it reaches a minimum, denoted as Min in FIG. **22**B, then starts increasing thereafter. $\Delta R/\Delta P$ deviates (drops) from the linear trend **910** first before it reaches the minimum, Min. This signature indicates the cooling caused by initiation of the head-media contact. The minimum point, Min, indicates full head-media contact and that heat is generated by friction.

It can be appreciated that performing accurate direct resistance measurements with DC current can be challenging for the drive electronics. For example, sensor resistance changes caused by the interface heating and cooling condition change is typically less than about 10% of its mean resistance. Considering the resolution of the analog-to-digital converter (ADC) in a typical drive is 8 bits, it would be difficult to measure the resistance directly to less than 0.01 Ohm accuracy.

With reference to FIG. **23**, one approach according to various embodiments involves measuring the $\Delta R/\Delta P$ directly in hard disk drive. Such an approach uses an analog switch as a modulator to modulate the heater element power and uses phase sensitive detection (PSD) to lock in the frequency to detect the resistance change from the resistance temperature sensor.

A direct measurement of the $\Delta R/\Delta P$ can be achieved by a scheme implemented by the representative circuit **1000** shown in FIG. **23**. In the embodiment shown in FIG. **23**, an analog switch **1004** is coupled to a power circuit **1006** of a heater element **1008**. The heater element power in a hard disk drive is proportional to the DAC counts, shown as an input **1001** to the analog switch **1004**. If the input **1005** of the heater element power circuit **1006** is switched (e.g., modulated) at a fixed frequency between the direct DAC output on input **1001** and an offset, ΔV, from the DAC output **1001** on a second input **1002**, the heater element power will be modulating between P and P-DP. A phase sensitive detection circuit **1024**, coupled to a resistance temperature sensor **1020** via a preamplifier **1022**, can be used to measure the resistance temperature sensor response at the modulation frequency, which would be the ΔR caused by this ΔP. The noise on $\Delta R/\Delta P$ is significantly reduced by pulsing the heater element **1008** and using a PSD device **1024** to measure the resistance temperature sensor response.

Therefore, head-media contact can be detected by monitoring the ΔR response of the resistance temperature sensor **1020**, which is preferably a TCR sensor situated at or near the close point. The modulation frequency can be as high as over 10 kHz and the measurement on ΔR can be done very fast and with great accuracy, because it is not limited by the heater element time constant.

Other embodiments are directed to driving the heater element **1008** with alternating current. For example, the heater element **1008** can be driven with alternating current at a desired frequency (e.g., ~50 kHz to ~80 kHz) by appropriately configuring the DAC of the heater element power circuit **1006**, such as by programming software of the DAC. The detection circuit **1024** can be configured to measure the resistance temperature sensor response at the frequency of the alternating current that drives the heater element **1008**. Software control of the heater oscillation provides for increased flexibility to specify the waveform applied to the heater element **1008**. This allows use of a variety of waveforms to drive the heater element **1008**, including square, sine, triangle, or other waveforms that can enhance the contact detection signal.

It is to be understood that even though numerous characteristics of various embodiments have been set forth in the foregoing description, together with details of the structure and function of various embodiments, this detailed description is illustrative only, and changes may be made in detail, especially in matters of structure and arrangements of parts illustrated by the various embodiments to the full extent indicated by the broad general meaning of the terms in which the appended claims are expressed.

What is claimed is:

1. An apparatus, comprising:
- a head transducer configured to interact with a magnetic recording medium, a low-modulation or a non-modulation head-to-medium interface defined between the head transducer and the medium;
- a heater configured to actuate the head transducer;
- a modulator coupled to the heater and configured to modulate power supplied to the heater at a modulation frequency of greater than 10 kHz;
- a sensor situated at the head transducer and having a temperature coefficient of resistance, the sensor configured to sense for contact between the head transducer and the medium; and
- a detector coupled to the sensor, the detector configured to measure a response of the sensor and detect head-medium contact using a detection metric based on a change in resistance of the sensor and a change in heater power.

2. The apparatus of claim **1**, wherein the detector is configured to measure the response of the sensor at the modulation frequency.

3. The apparatus of claim **1**, wherein the detection metric is based on a rate of change in resistance of the sensor and a rate of change in heater power.

4. The apparatus of claim **1**, wherein the detection metric is defined by a ratio ΔR/ΔP, where ΔR is a rate of change in resistance of the sensor and ΔP is a rate of change in heater power.

5. The apparatus of claim **4**, wherein the detector is configured to make an in situ measurement of ΔR/ΔP.

6. The apparatus of claim **1**, wherein the detector comprises a phase sensitive detector.

7. The apparatus of claim **1**, wherein the detector is configured to detect head-medium contact by detecting a minimum of the detection metric.

8. The apparatus of claim **1**, wherein the detector is configured to detect onset of head-medium contact by detecting a deviation from a linear decrease in the detection metric prior to the detection metric reaching a minimum.

9. The apparatus of claim **1**, wherein the sensor is configured to receive DC current, and the detector is configured to measure a change in sensor resistance using DC sensor current.

10. The apparatus of claim **1**, wherein the heater comprises a heater element and a power circuit comprising a digital-to-analog converter (DAC), the power circuit configured to drive the heater element with alternating current at the modulation frequency controlled by the DAC.

11. The apparatus of claim **1**, wherein the head-to-medium interface defines a beyond contact recording head-to-medium interface.

12. A method, comprising:
- modulating, at a modulation frequency of greater than 10 kHz, power supplied to a heater of a head transducer configured to interact with a magnetic recording medium, a low-modulation or a non-modulation head-to-medium interface defined between the head transducer and the medium;
- sensing for contact between the head transducer and the medium using a sensor having a temperature coefficient of resistance;
- measuring a response of the sensor; and
- detecting head-medium contact using a detection metric based on a change in resistance of the sensor and a change in heater power.

13. The method of claim **12**, wherein measuring the sensor response comprises measuring the response of the sensor at the modulation frequency.

14. The method of claim **12**, wherein the detection metric is based on a rate of change in resistance of the sensor and a rate of change in heater power.

15. The method of claim **12**, wherein the detection metric is defined by a ratio ΔR/ΔP, where ΔR is a rate of change in resistance of the sensor and ΔP is a rate of change in heater power.

16. The method of claim **15**, wherein:
- the method is performed by a disk drive; and
- measuring the sensor response comprises making an in situ measurement of ΔR/ΔP by the disk drive.

17. The method of claim **12**, wherein detecting head-medium contact comprises detecting a minimum of the detection metric.

18. The method of claim **12**, further comprising detecting onset of head-medium contact by detecting a deviation from a linear decrease in the detection metric prior to the detection metric reaching a minimum.

19. The method of claim **12**, wherein:
- sensing for contact comprises receiving DC current by the sensor; and
- measuring the response of the sensor comprises measuring a change in sensor resistance using DC sensor current.

20. The method of claim **12**, wherein the head-to-medium interface defines a beyond contact recording head-to-medium interface.

21. The apparatus of claim **1**, wherein the modulation frequency ranges between about 50 kHz and about 80 kHz.

22. The method of claim **12**, wherein the modulation frequency ranges between about 50 kHz and about 80 kHz.

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